Solar Corona and Heliosphere

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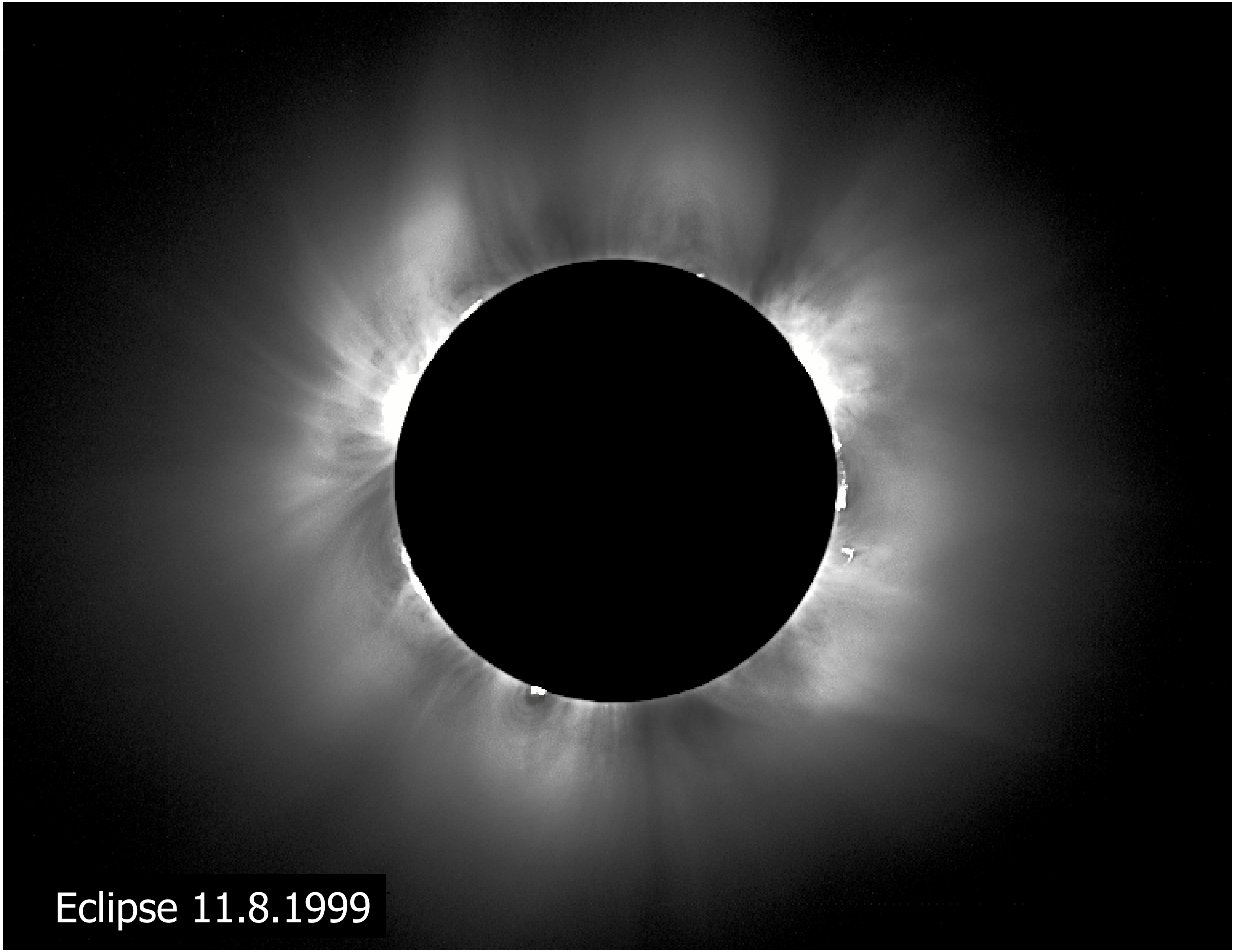
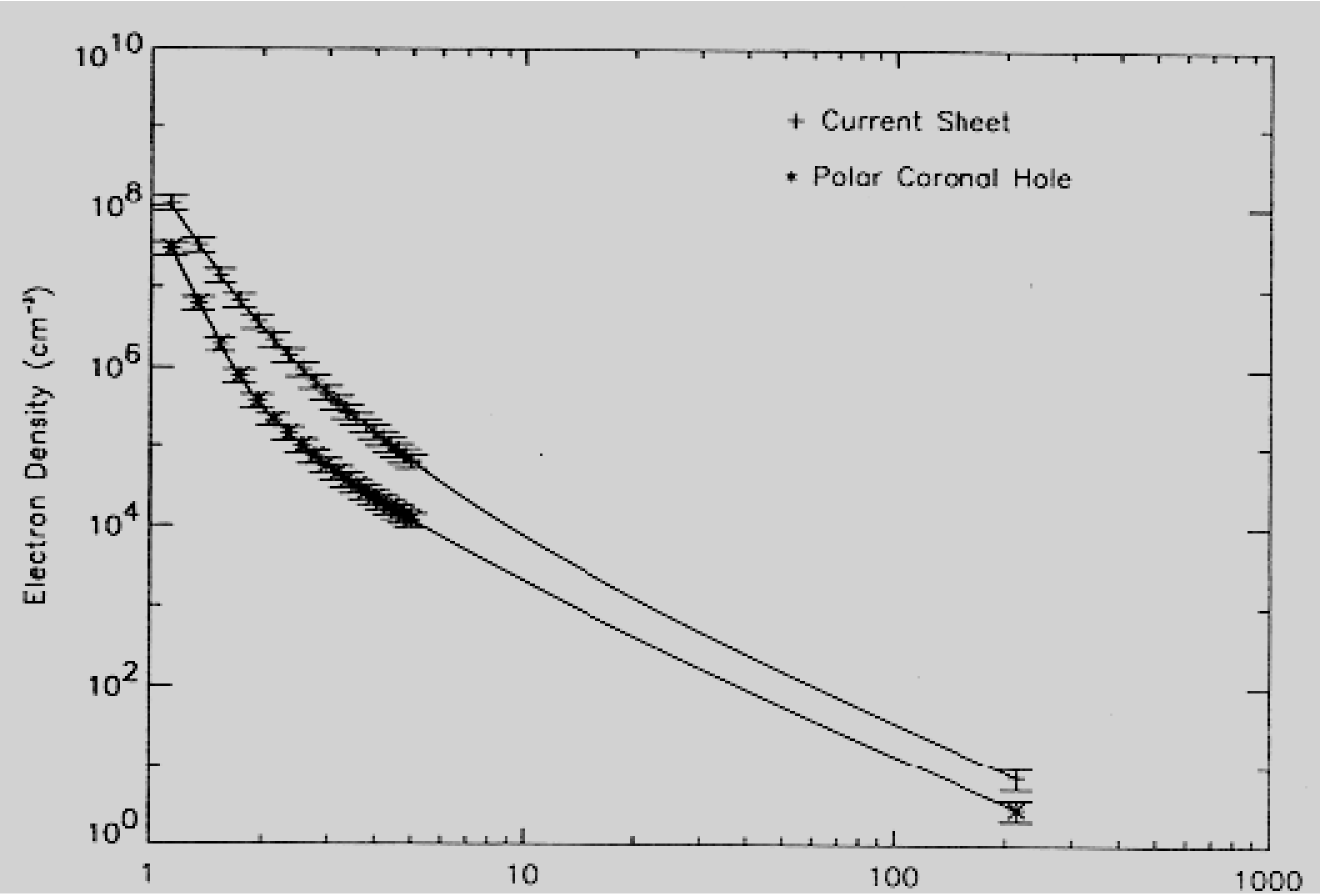
- **The Sun’s corona and solar wind - structure, evolution and dynamics of the heliosphere**
- **Waves and turbulence in the solar wind**
- **Temperatures in the corona and heliosphere**
- **Ions and electrons - velocity distributions, kinetic physics and fluid models**

The visible solar corona



Electron density in the corona



Heliocentric distance / R_s

+ Current sheet and streamer belt, closed

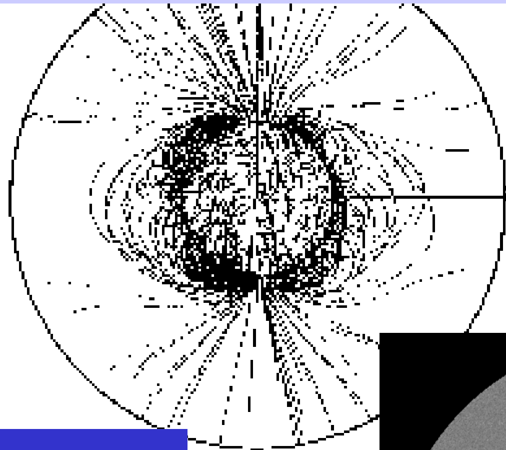
• Polar coronal hole, open magnetically

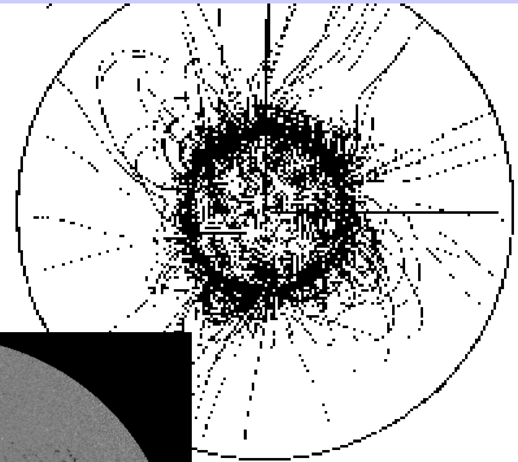
Guhathakurta and Sittler, 1999, Ap.J., **523**, 812

Skylab coronagraph/Ulysses in-situ

The coronal magnetic field

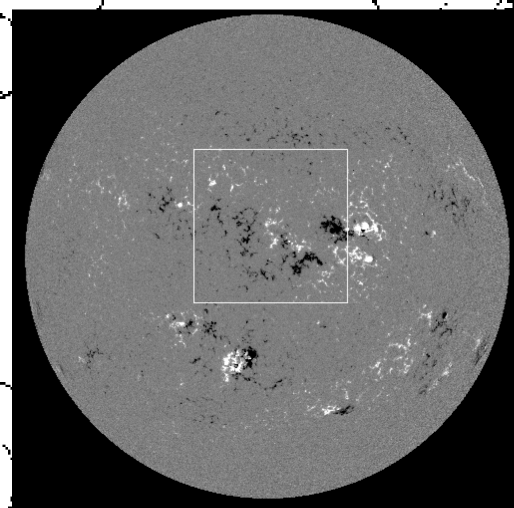
minimum



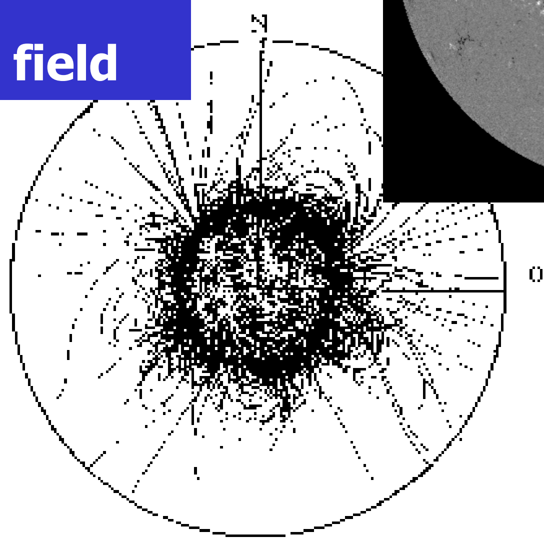


Model extrapolation:

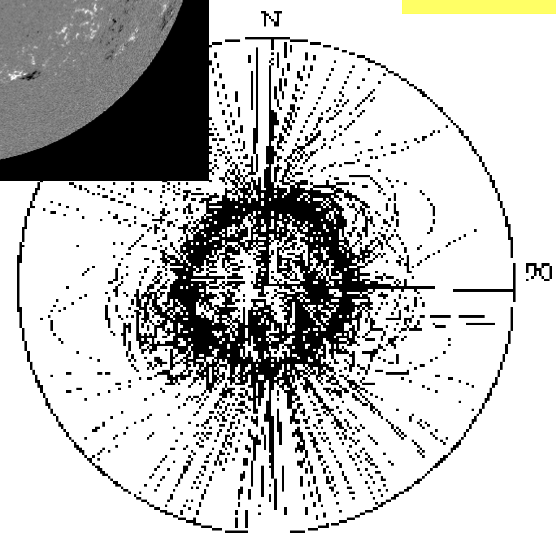
- **Potential field**
- **Force-free field**



Solar cycle variation



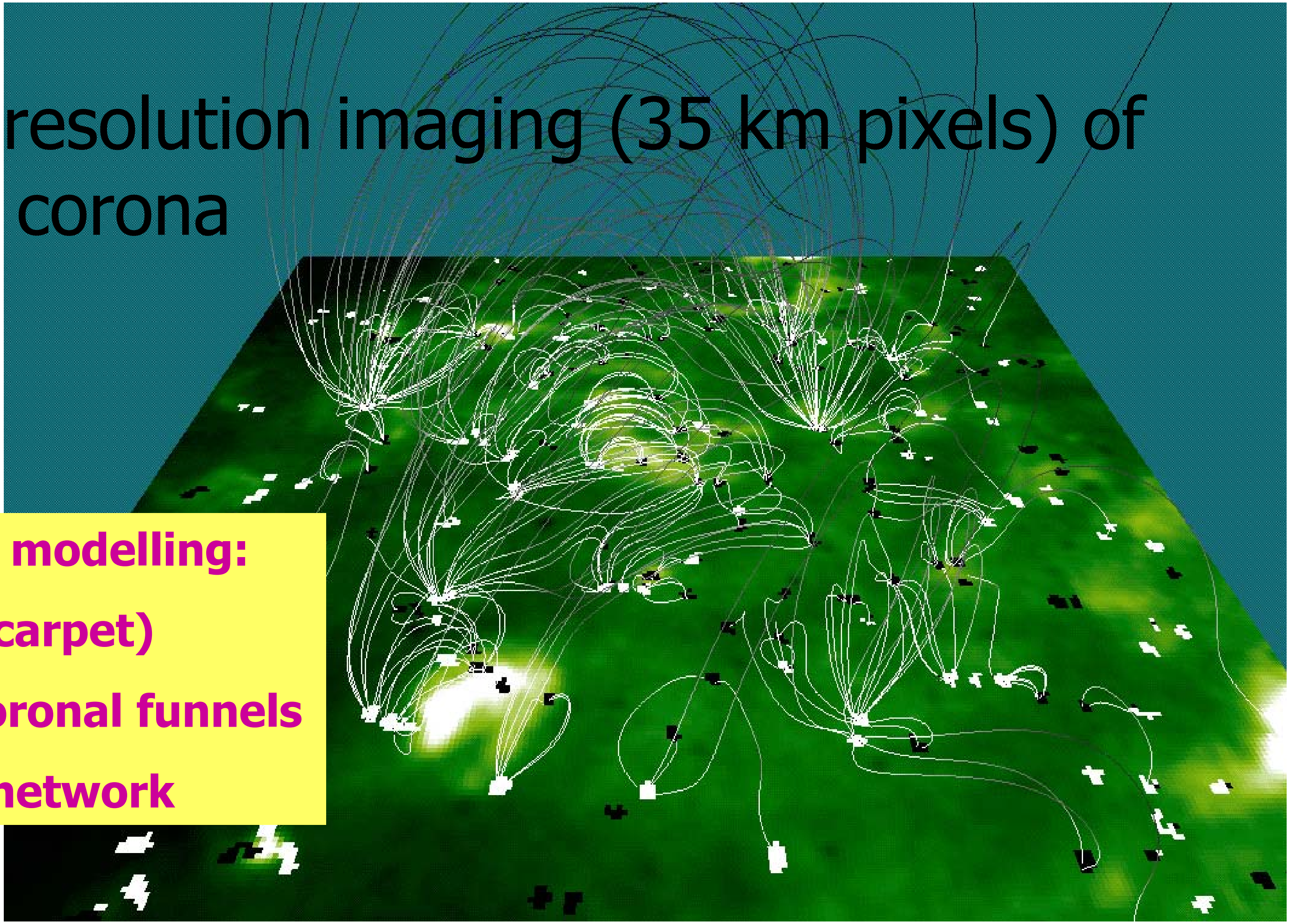
maximum



Bravo et al., 1998

The magnetic carpet

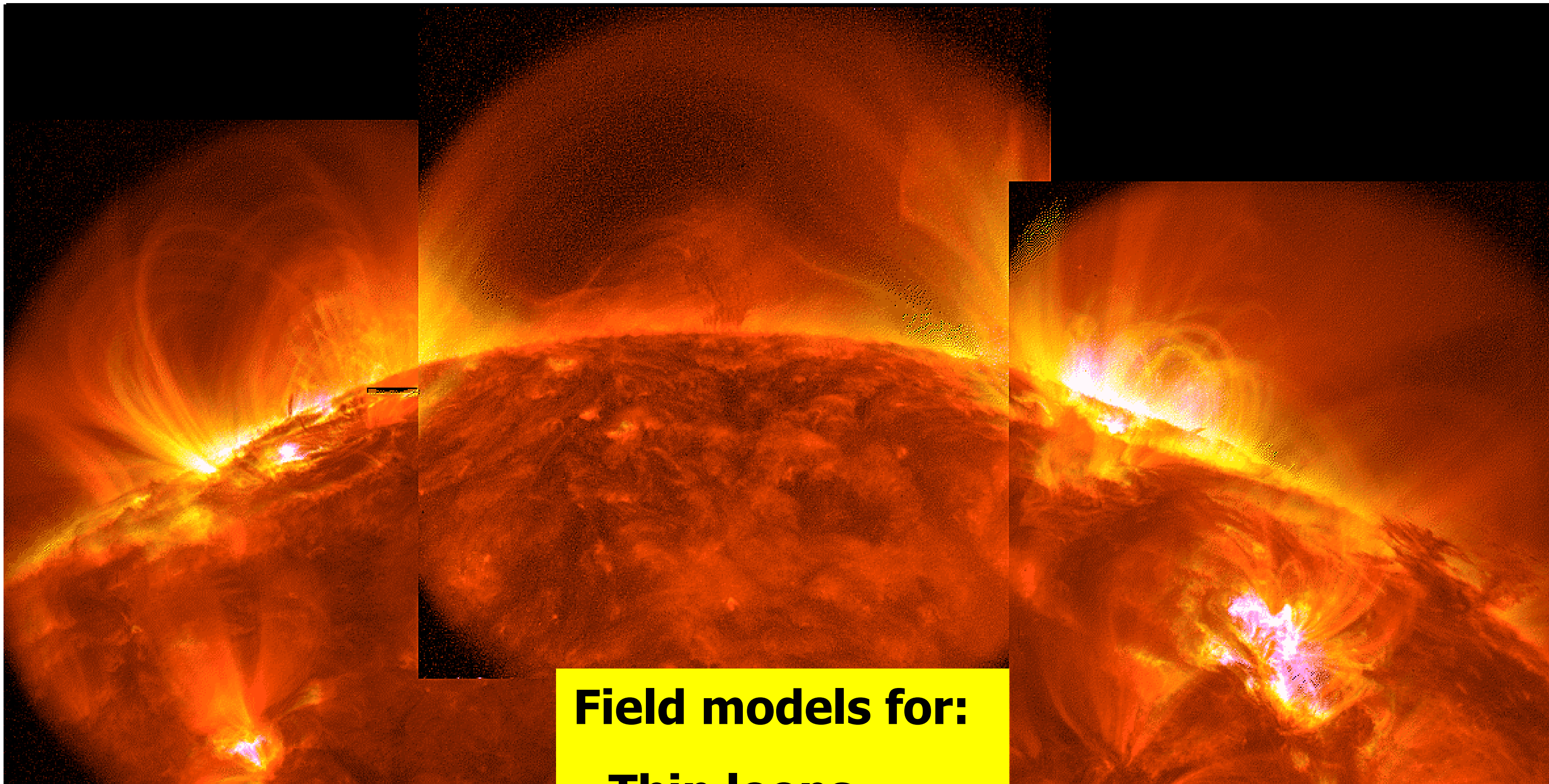
High-resolution imaging (35 km pixels) of the corona



Magnetic modelling:

- **Loops (carpet)**
- **Open coronal funnels**
- **Closed network**

Magnetic loops on the Sun

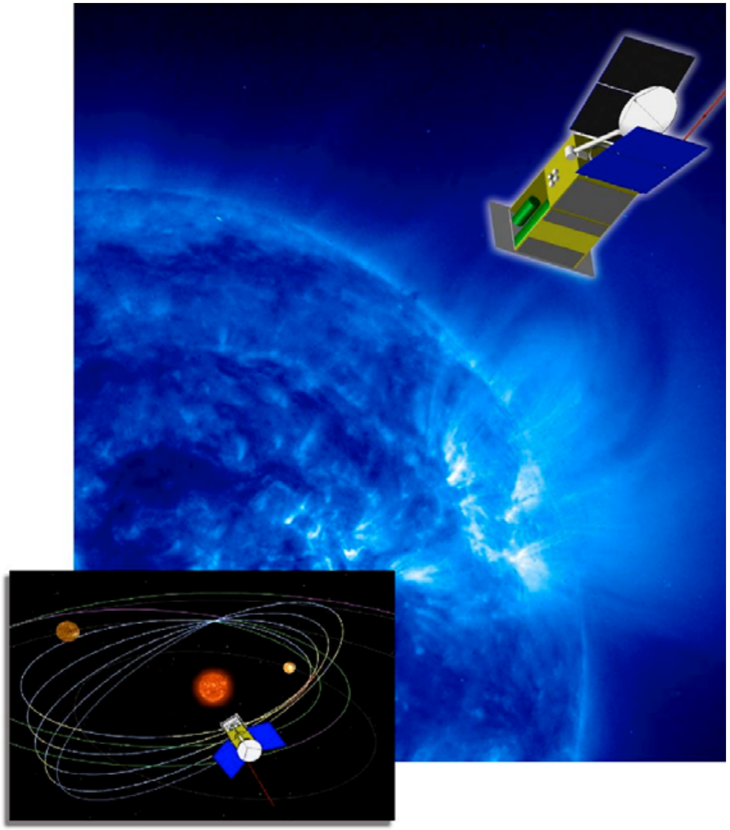


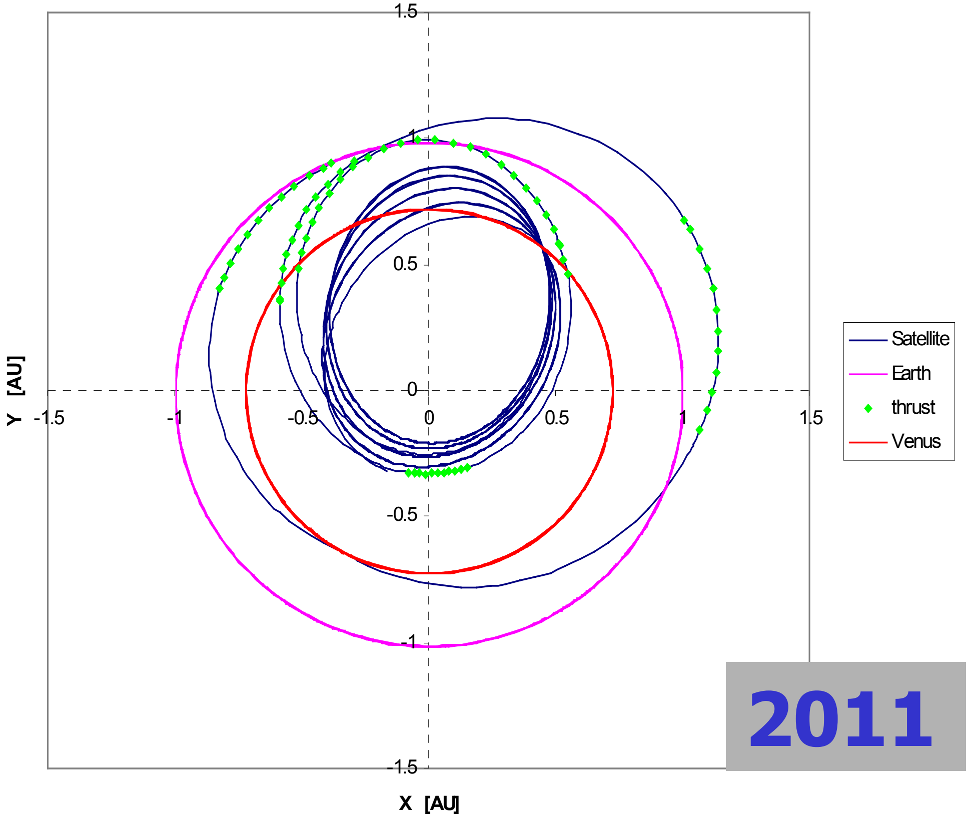
Field models for:

- **Thin loops**
- **Active regions**

TRACE

The inner frontier: Solar Orbiter

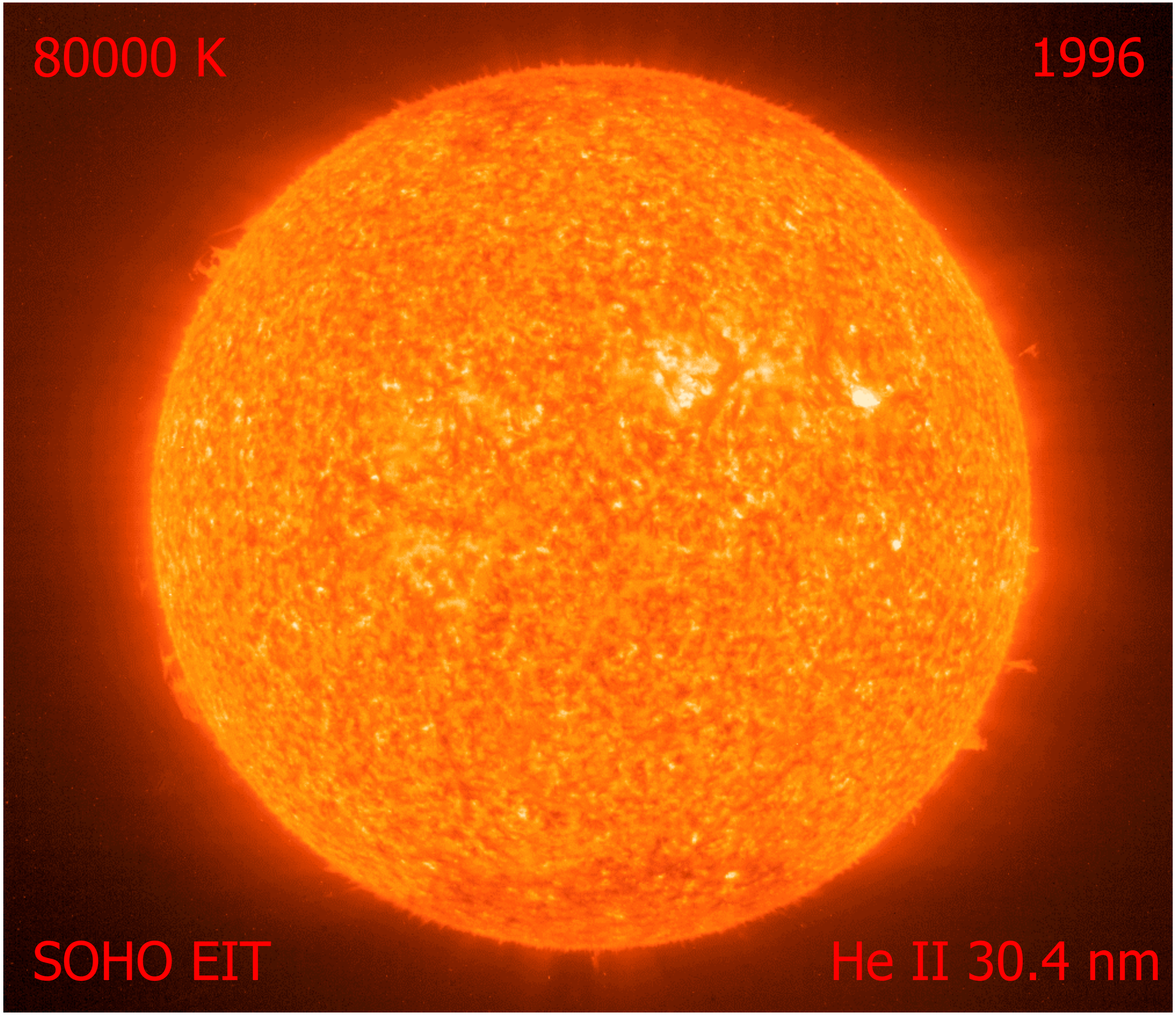




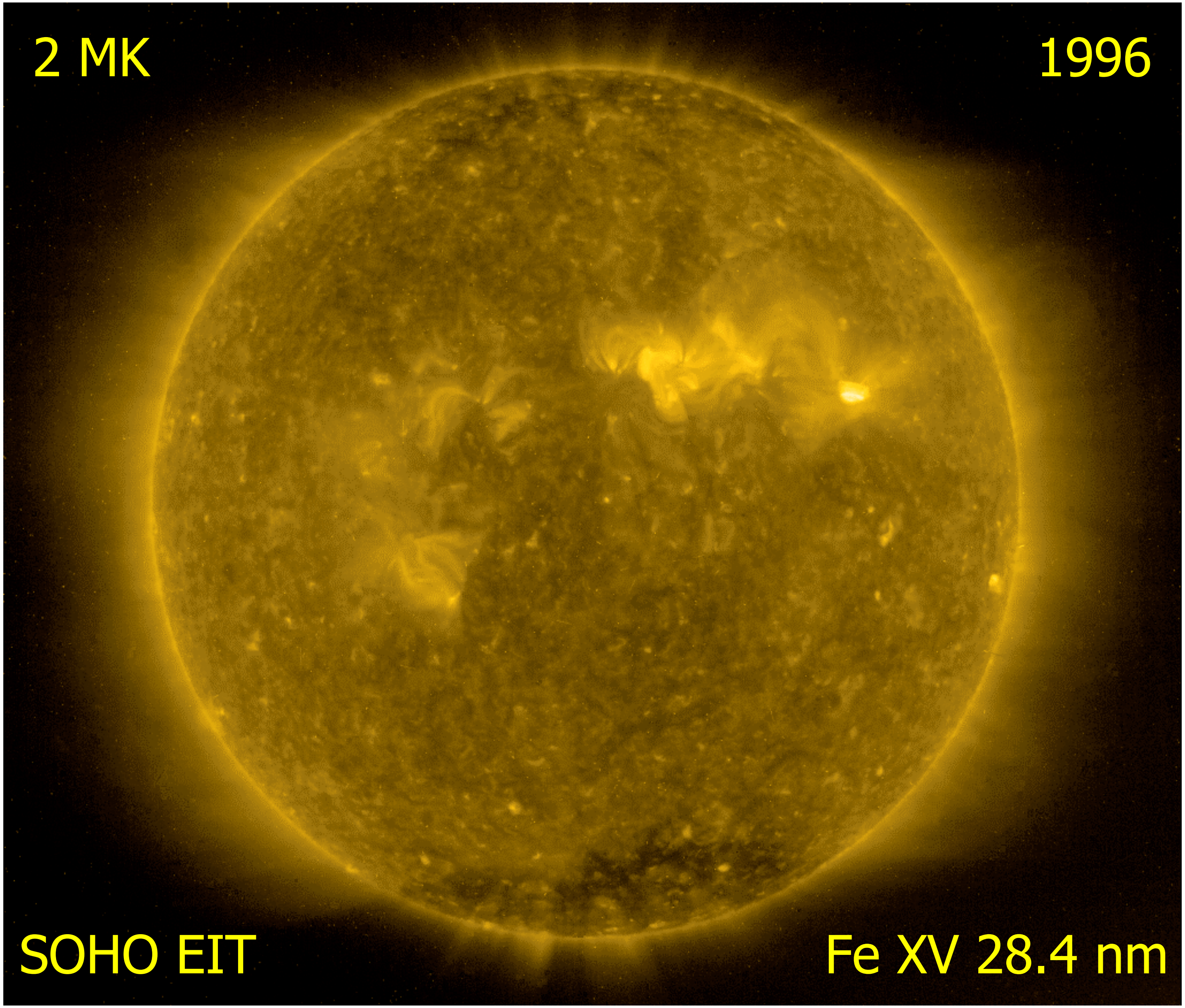
2011

A high-resolution mission to the Sun and inner heliosphere

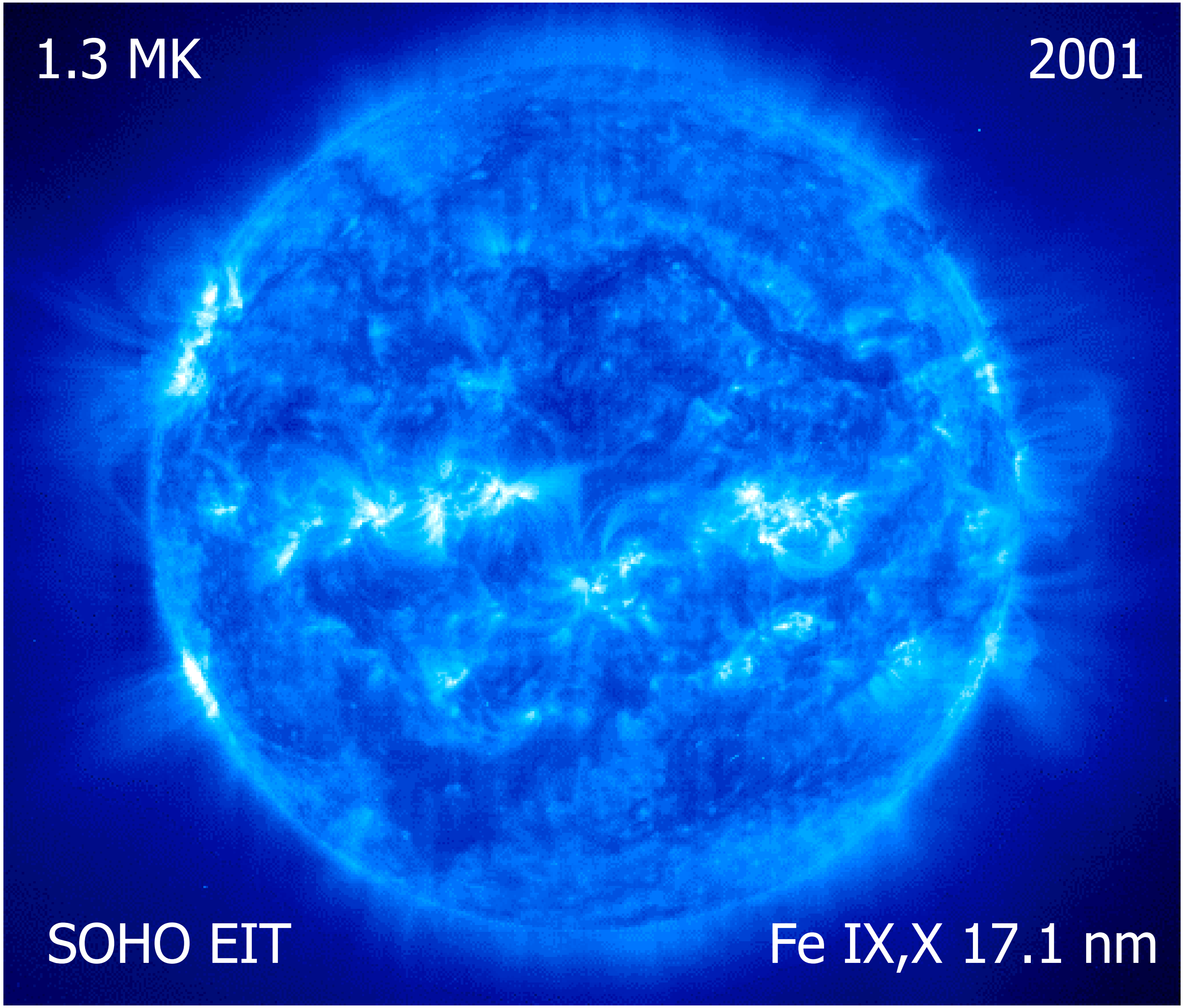
Corona and magnetic network



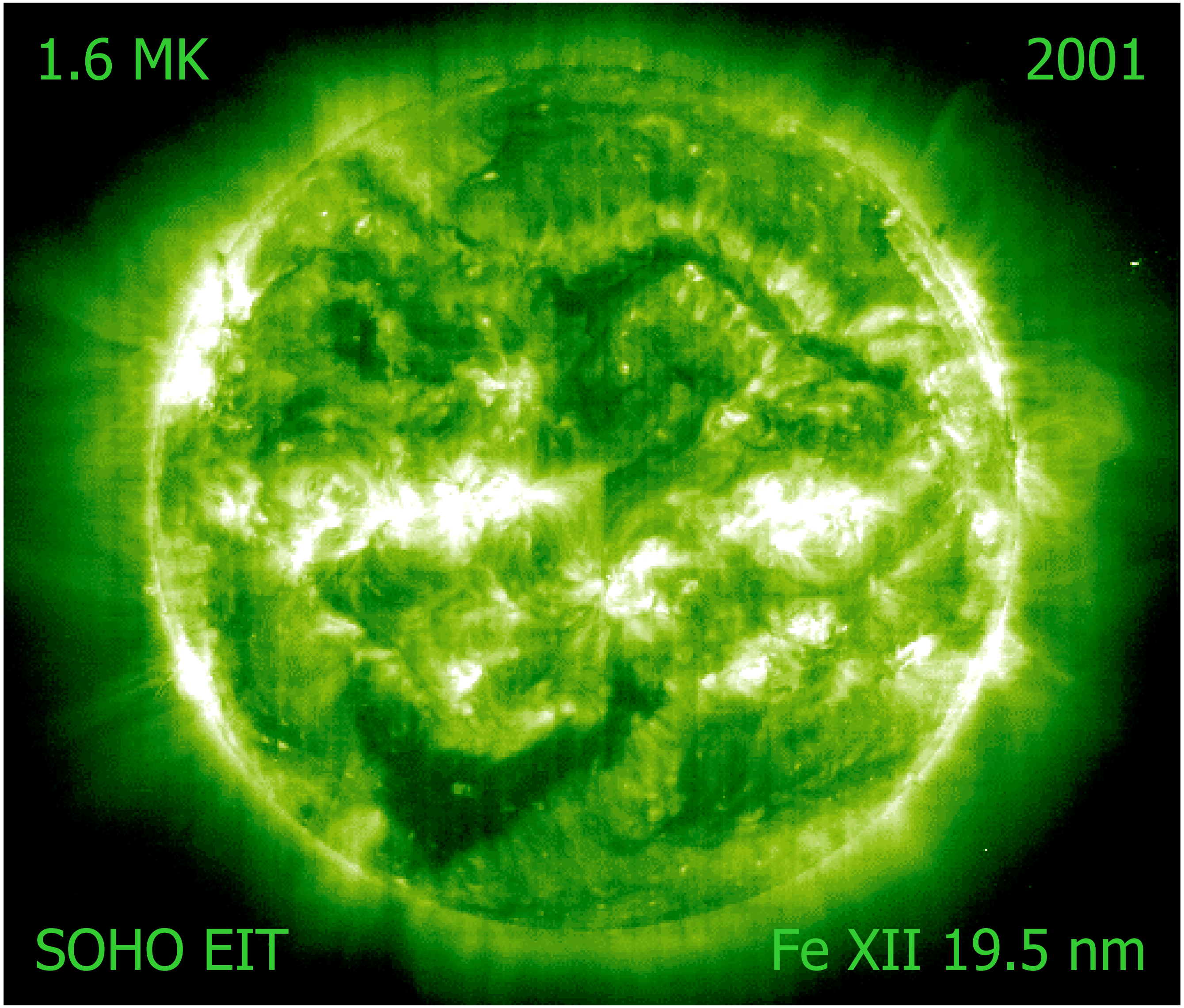
Active regions near minimum

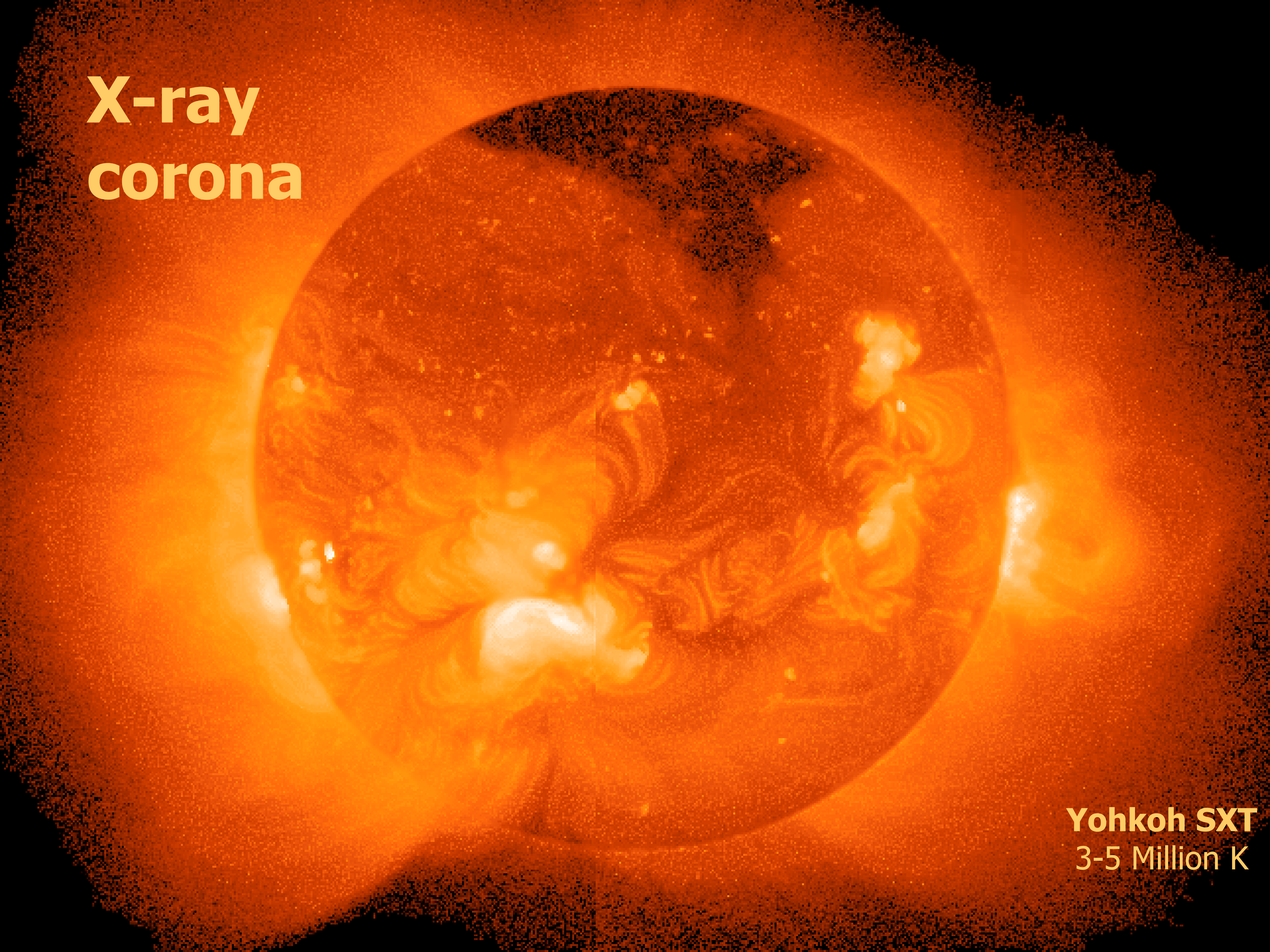


Corona and transition region

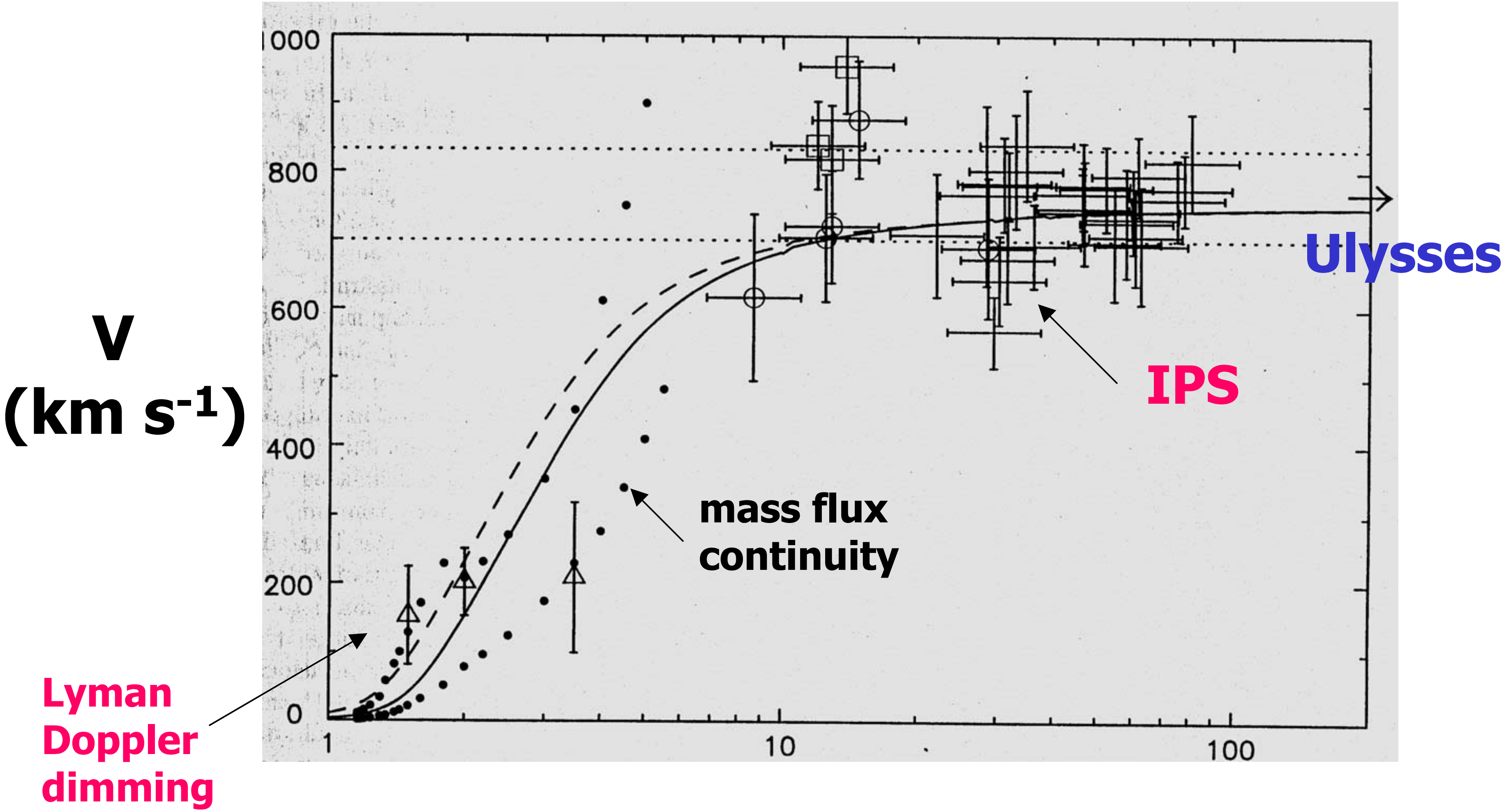


Active regions near maximum




X-ray
corona
Yohkoh SXT
3-5 Million K

Fast solar wind speed profile



Esser et al., ApJ, 1997

Fast solar wind parameters

- Energy flux at 1 R_S: $F_E = 5\ 10^5$ erg cm^{-2} s^{-1}
- Speed beyond 10 R_S: $V_p = (700 - 800)$ km s^{-1}
- Proton flux at 1 AU: $n_p V_p = 2\ 10^8$ cm^{-2} s^{-1}
- Density at 1 AU: $n_p = 3$ cm^{-3} ; $n_\alpha / n_p = 0.04$
- Temperatures at 1 AU:

  $T_p = 3\ 10^5$ K ; $T_\alpha = 10^6$ K ; $T_e = 1.5\ 10^5$ K
- Heavy ions: $T_i \cong m_i / m_p\, T_p$; $V_i - V_p = V_A$

Schwenn and Marsch, 1990, 1991

Rotation of solar corona

Fe XIV

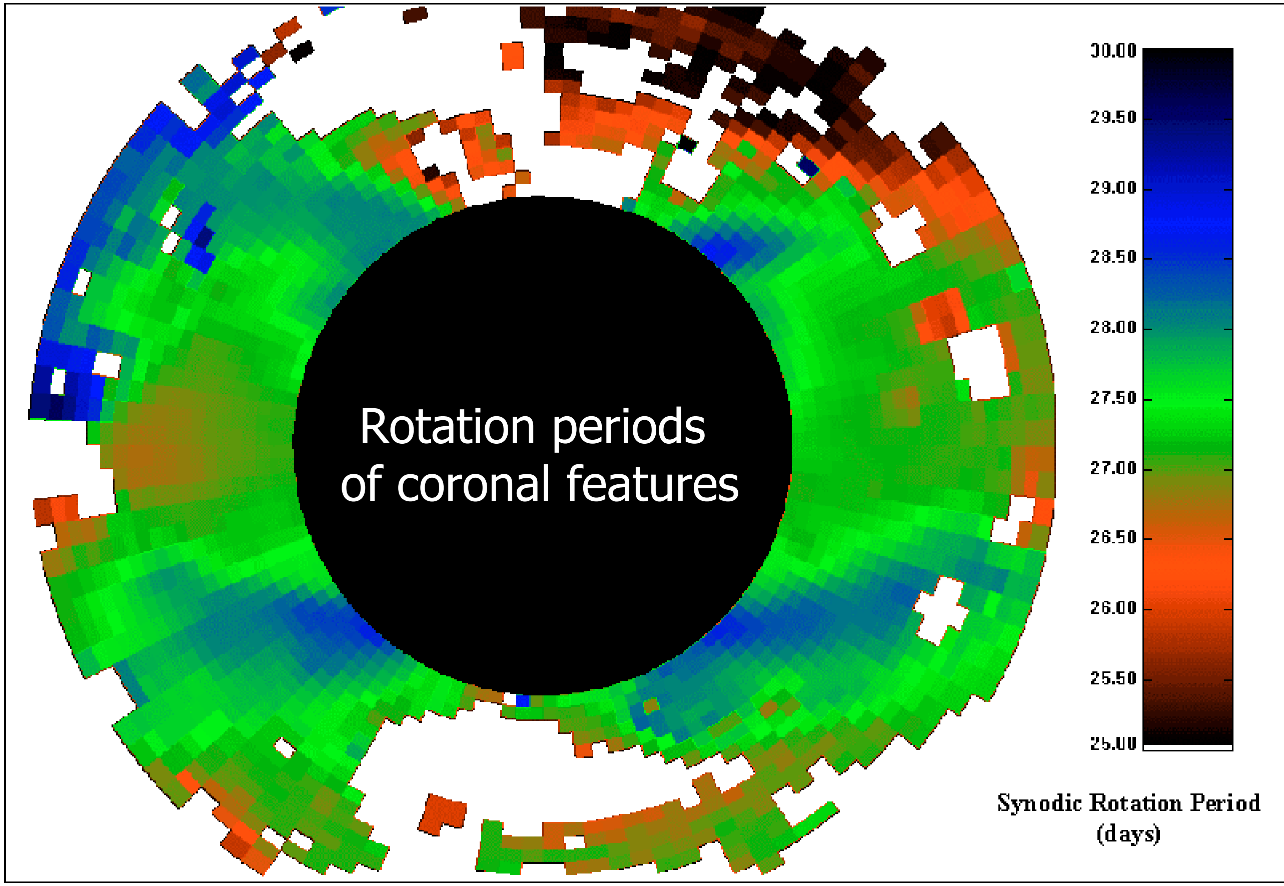
5303 Å

Time series:

1 image/day

(24-hour

averages)



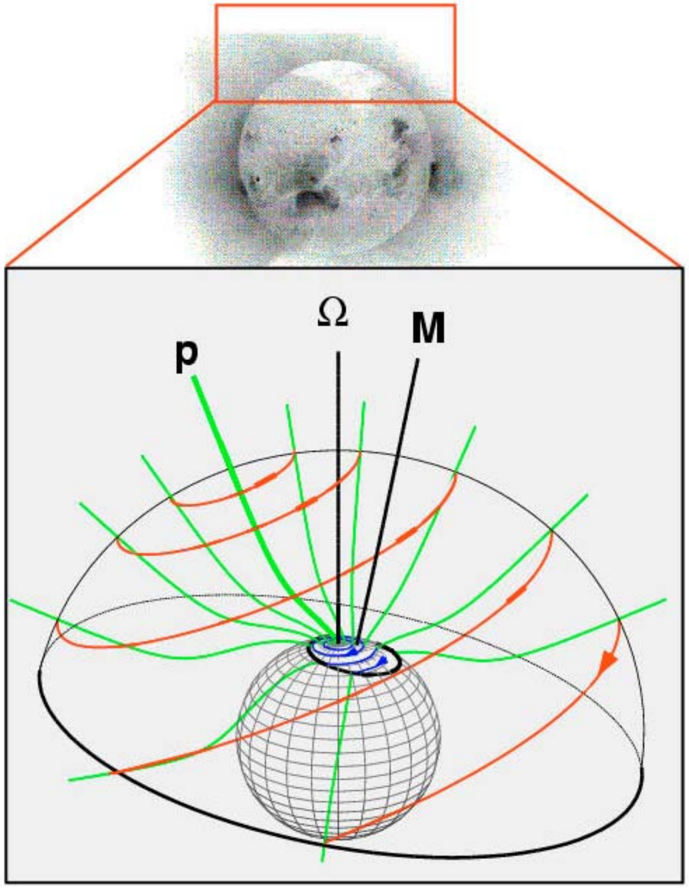
27.2 days

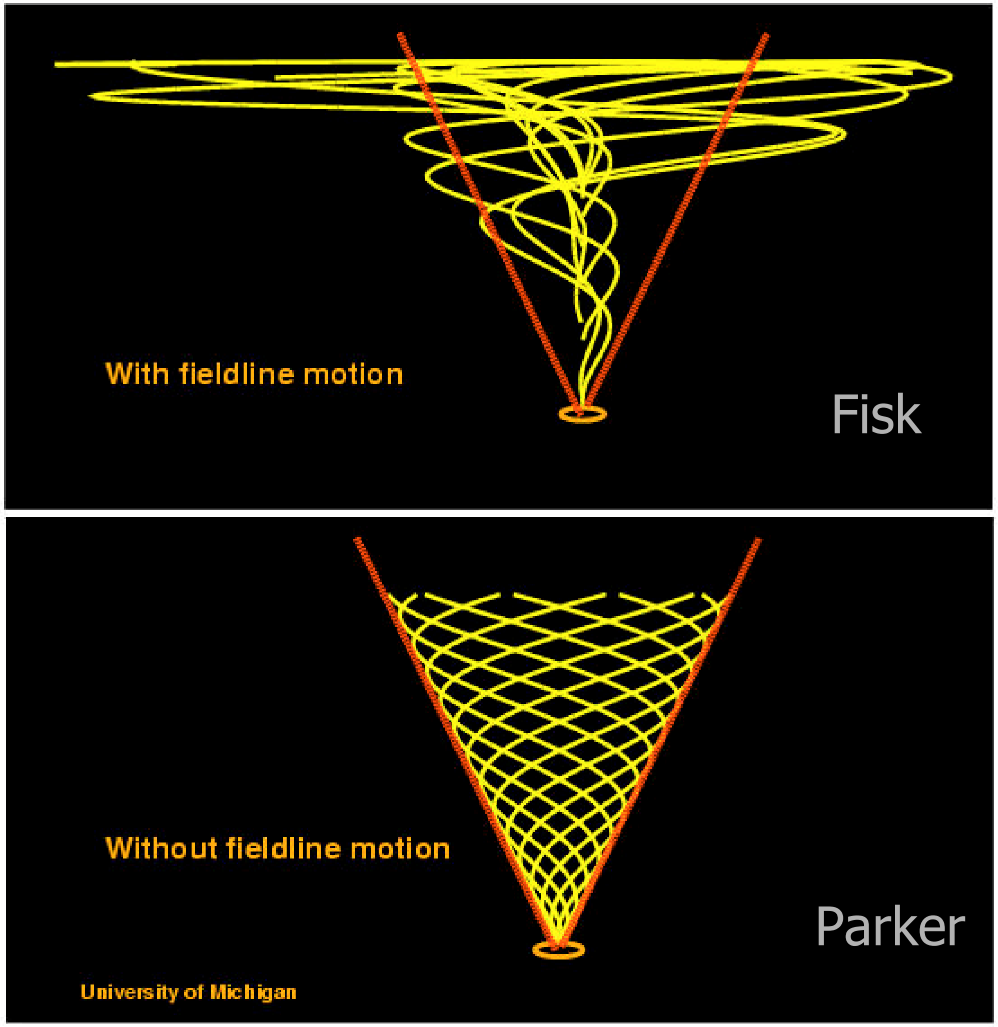
LASCO /SOHO

Stenborg et al., 1999

Long-lived coronal patterns exhibit uniform rotation at the equatorial rotation period!

Model of coronal-heliospheric field

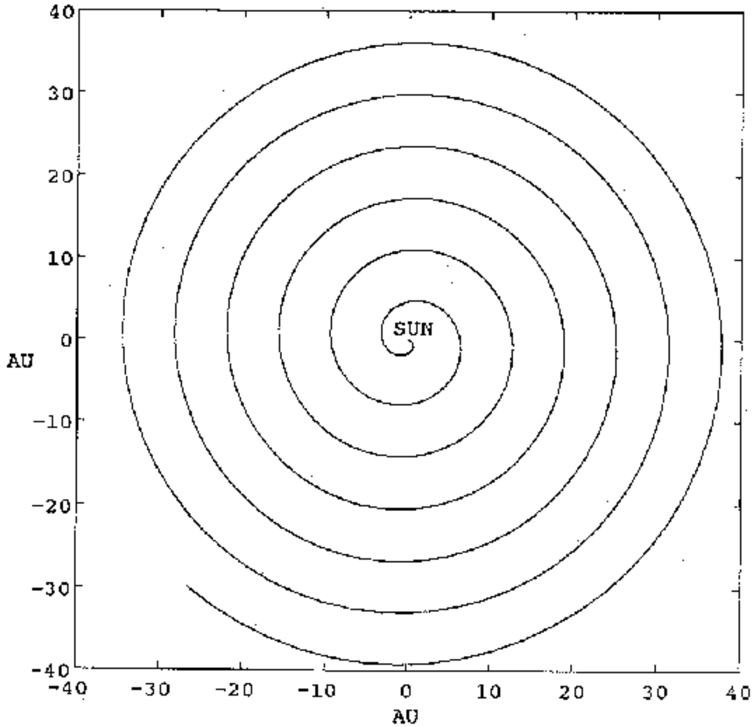


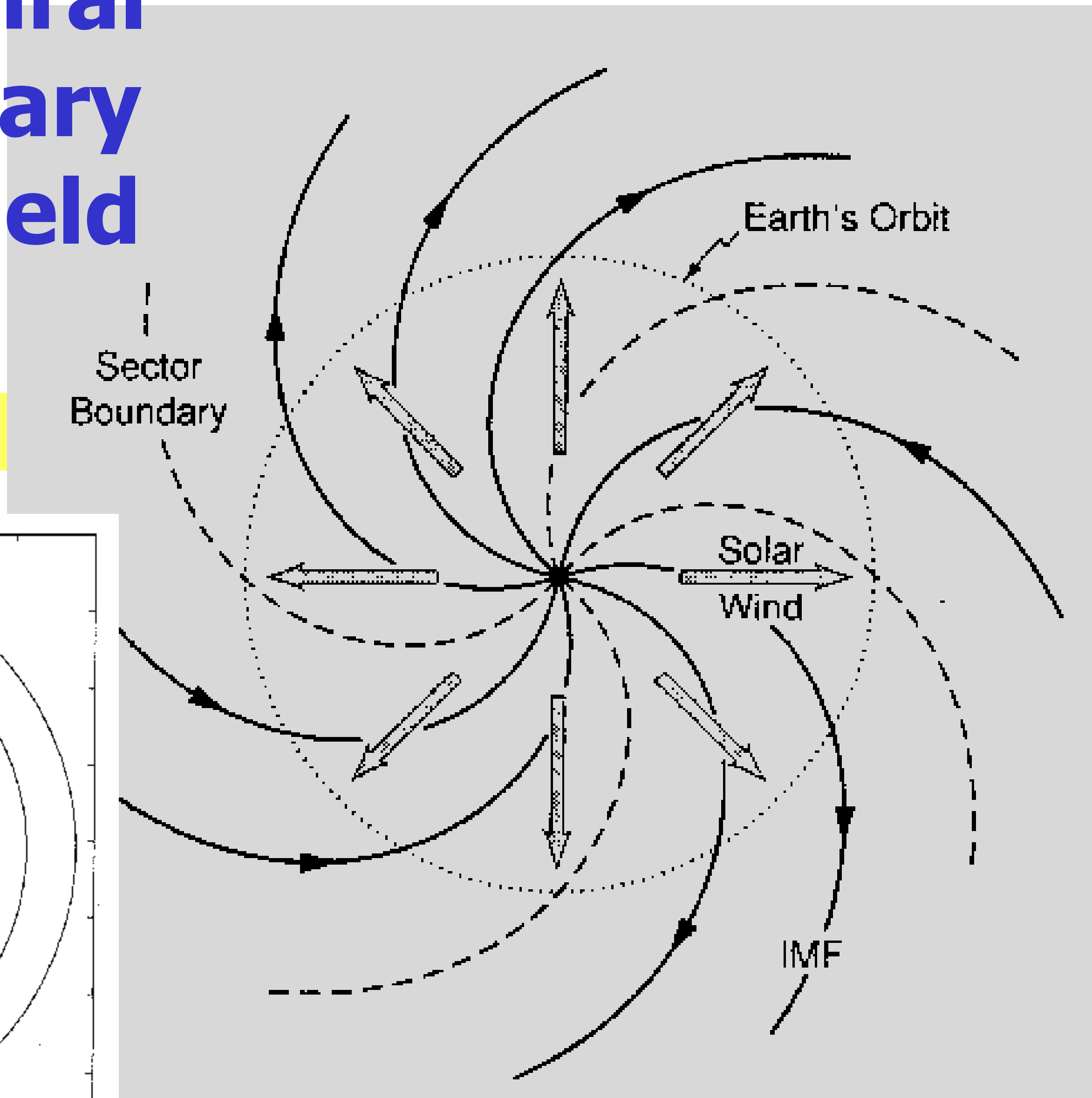


Fisk, JGR, 1996

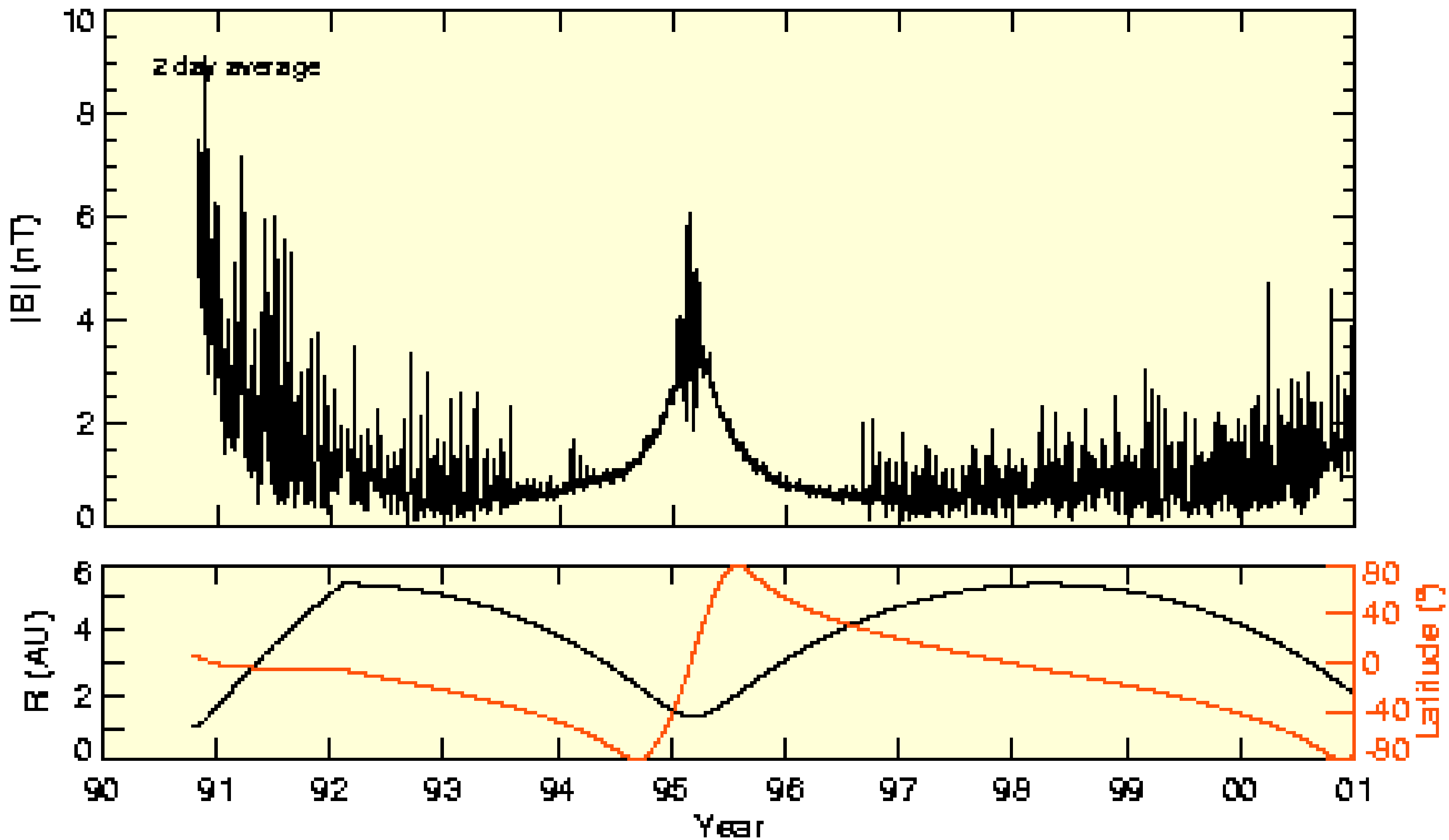
(Parker) spiral interplanetary magnetic field

rot(**E**) = rot(**V**X**B**) = **0**





Heliospheric magnetic field

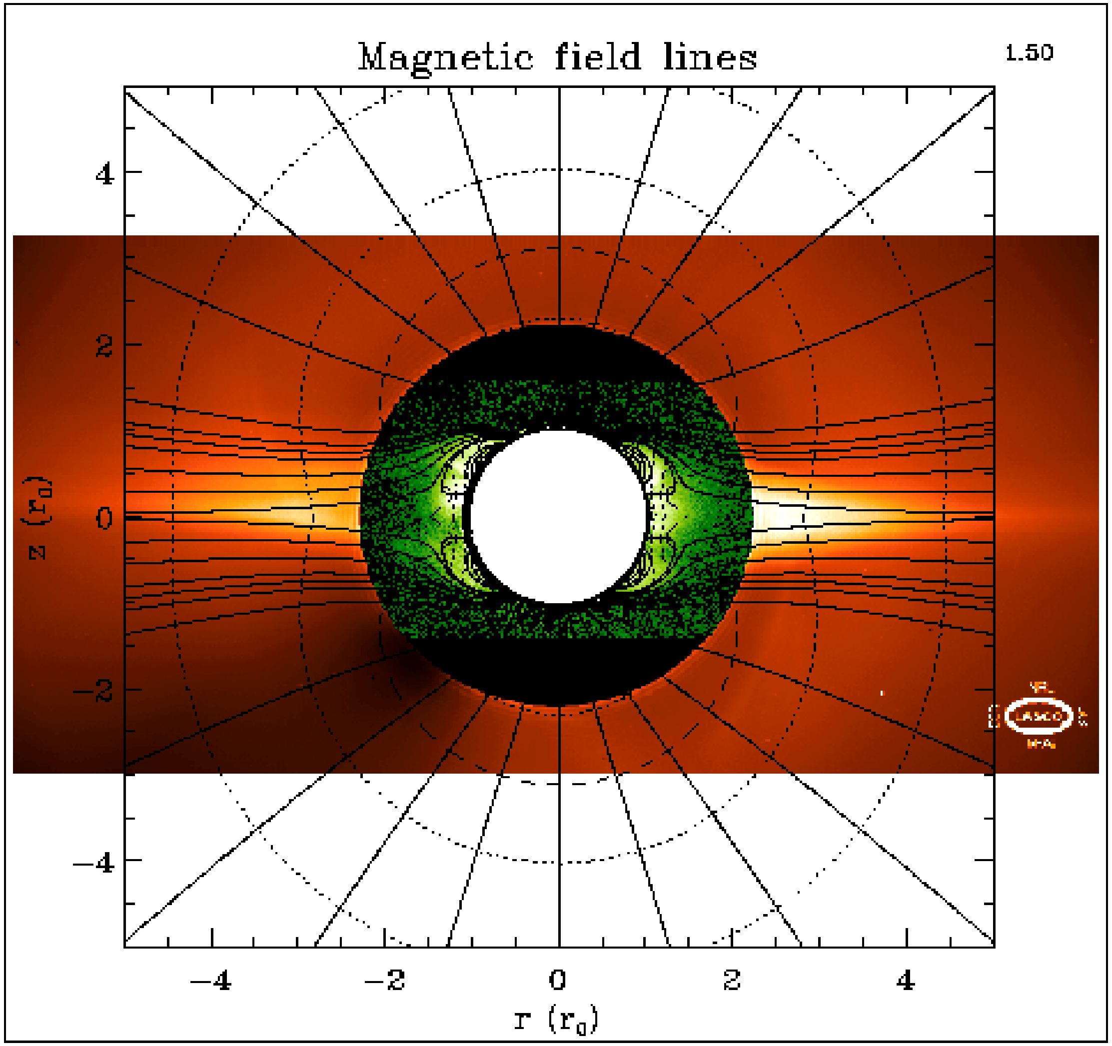


McComas et al., 1998

Ulysses SWOOPS

Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



Polar field: B = 12 G

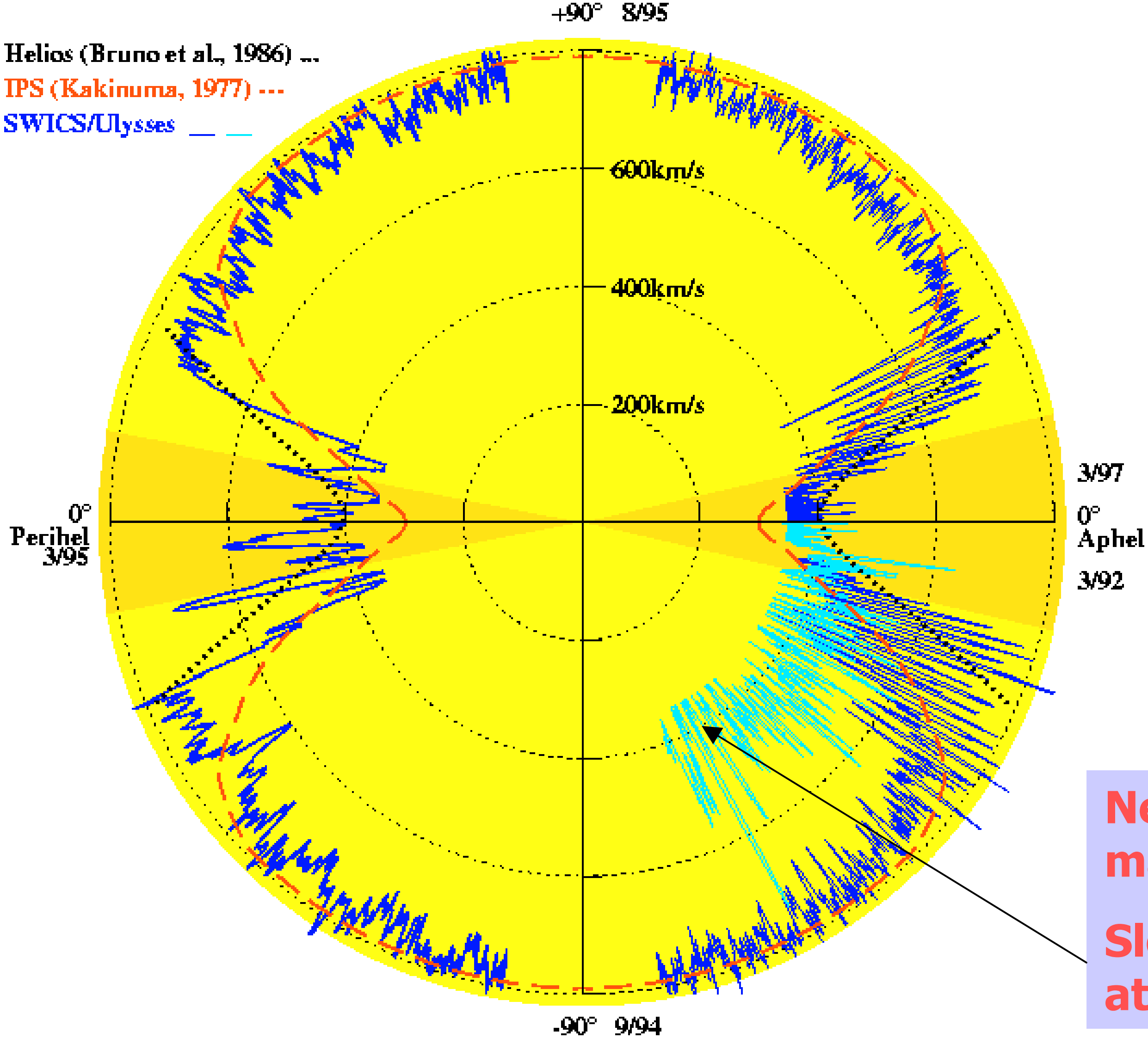
Current sheet is a symmetric disc anchored at high latitudes !

LASCO C1/C2 images (SOHO)

Banaszkiewicz et al., 1998;

Schwenn et al., 1997

Polar diagram of solar wind



SWICS

Ulysses

Ecliptic

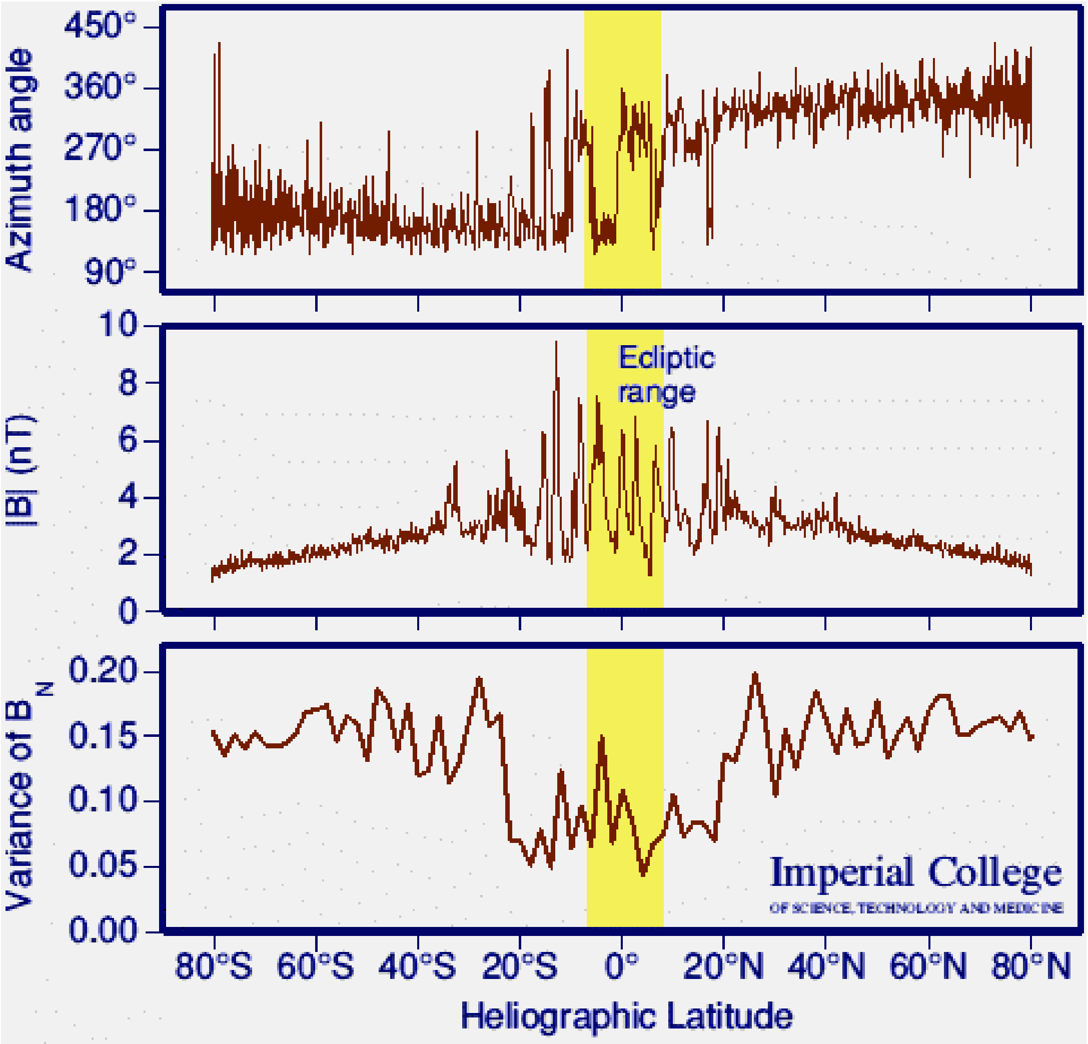
Near solar maximum:

Slow wind at - 65° !

Woch, 2000

Latitudinal variation of the heliospheric magnetic field

Ulysses

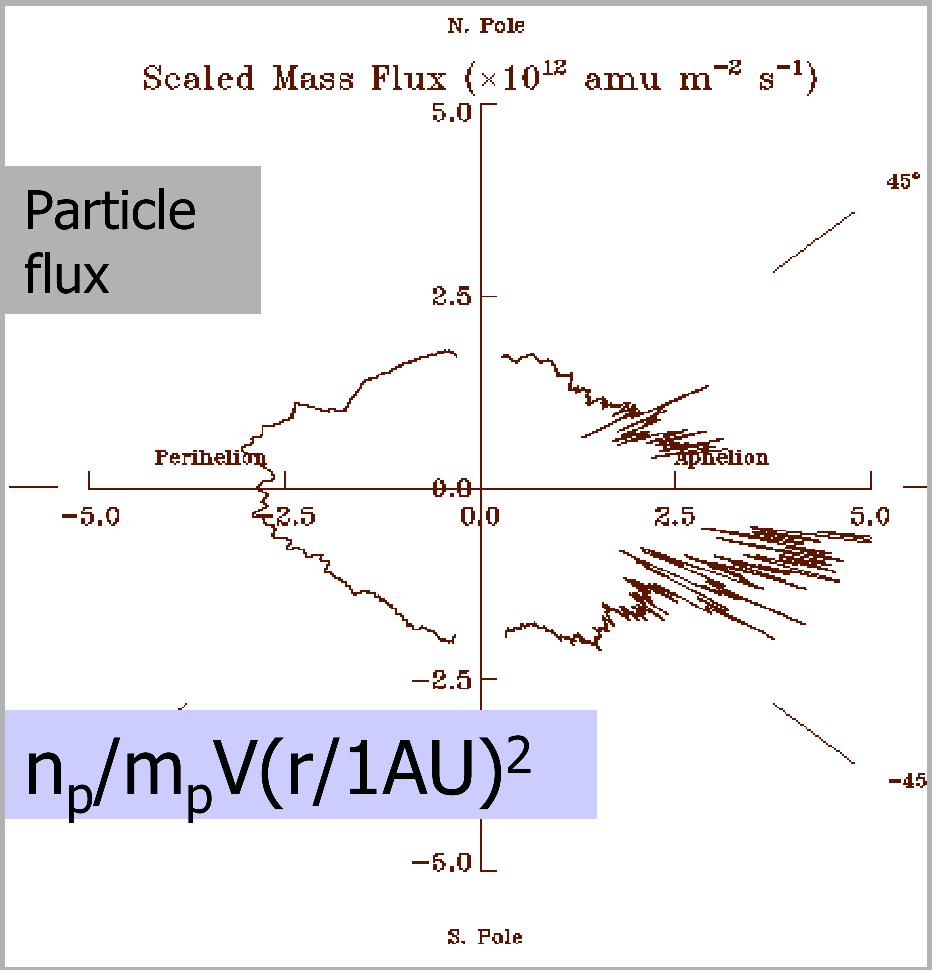


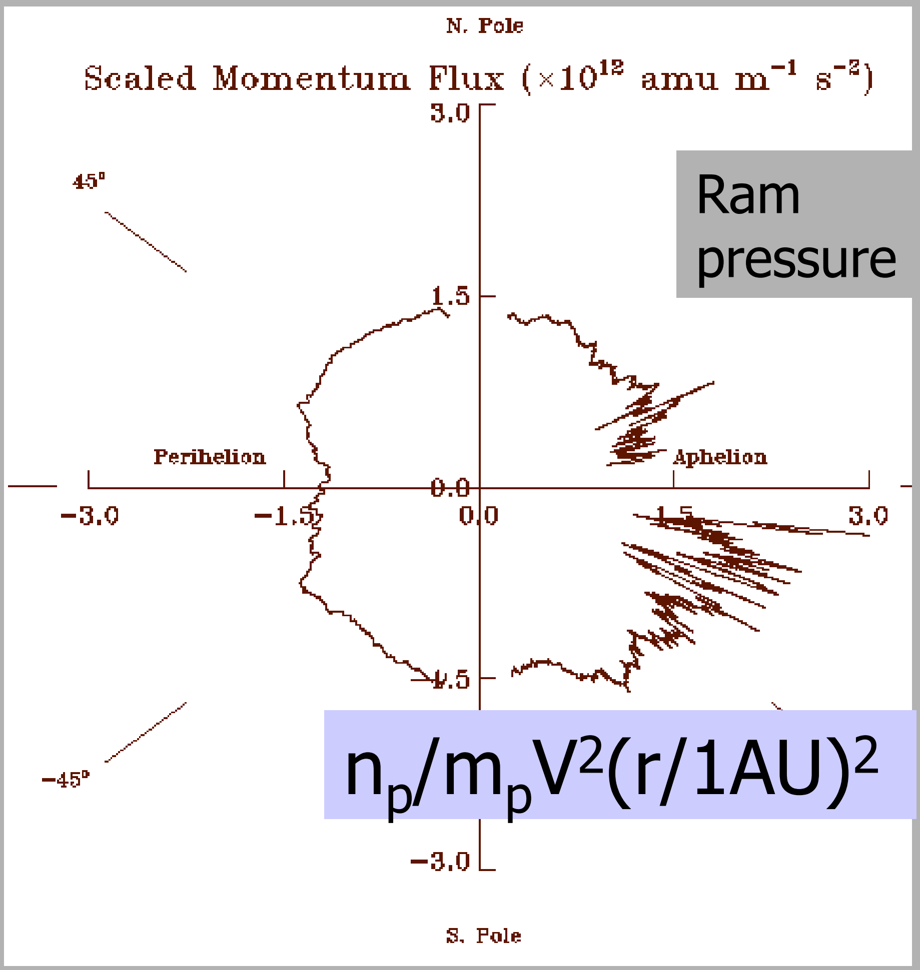
Field polarity

Alfvén waves

Balogh and Forsyth, 1998

Polar plot of mass/momentum flux

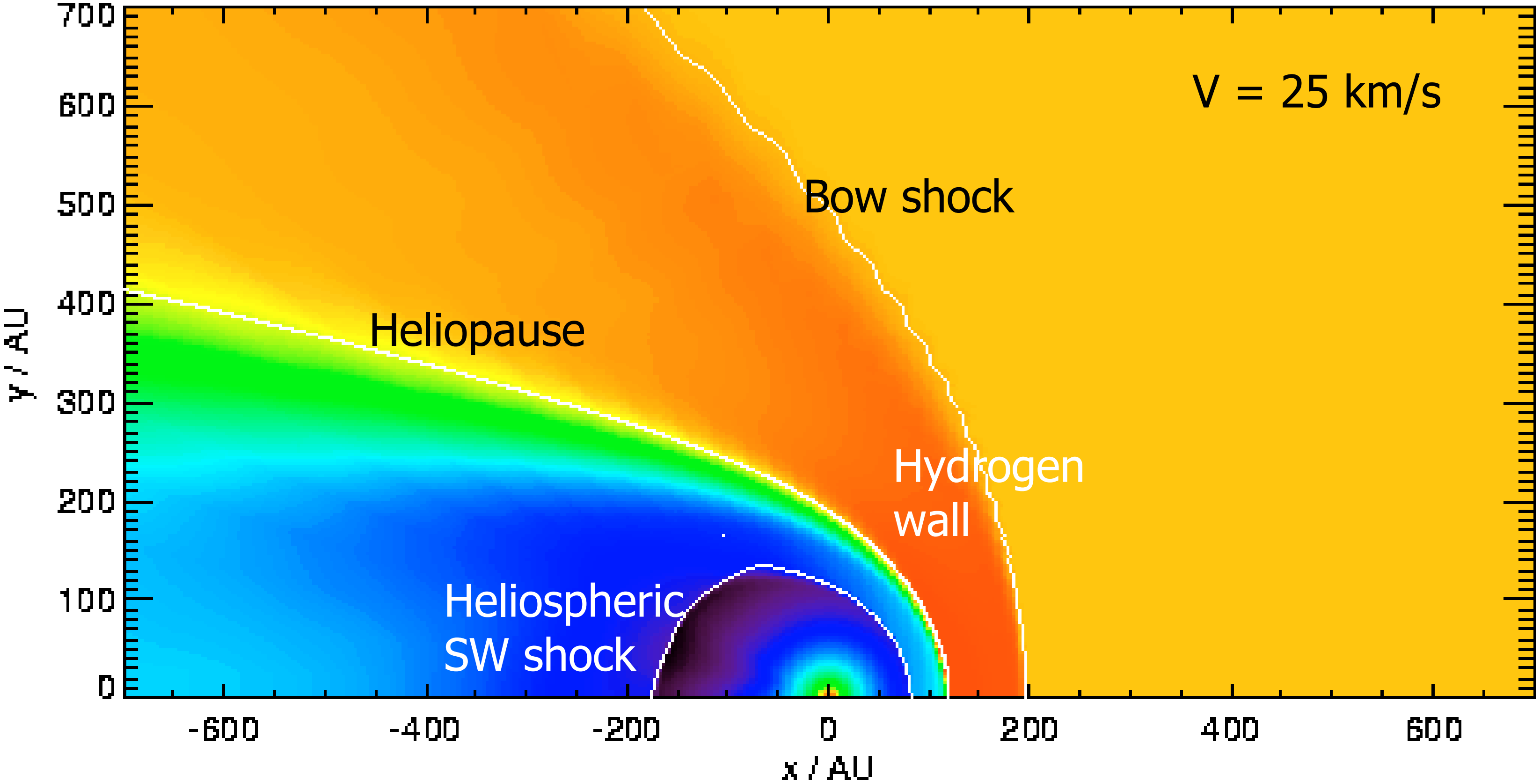




McComas et al., 1998

Ulysses SWOOPS/SWICS

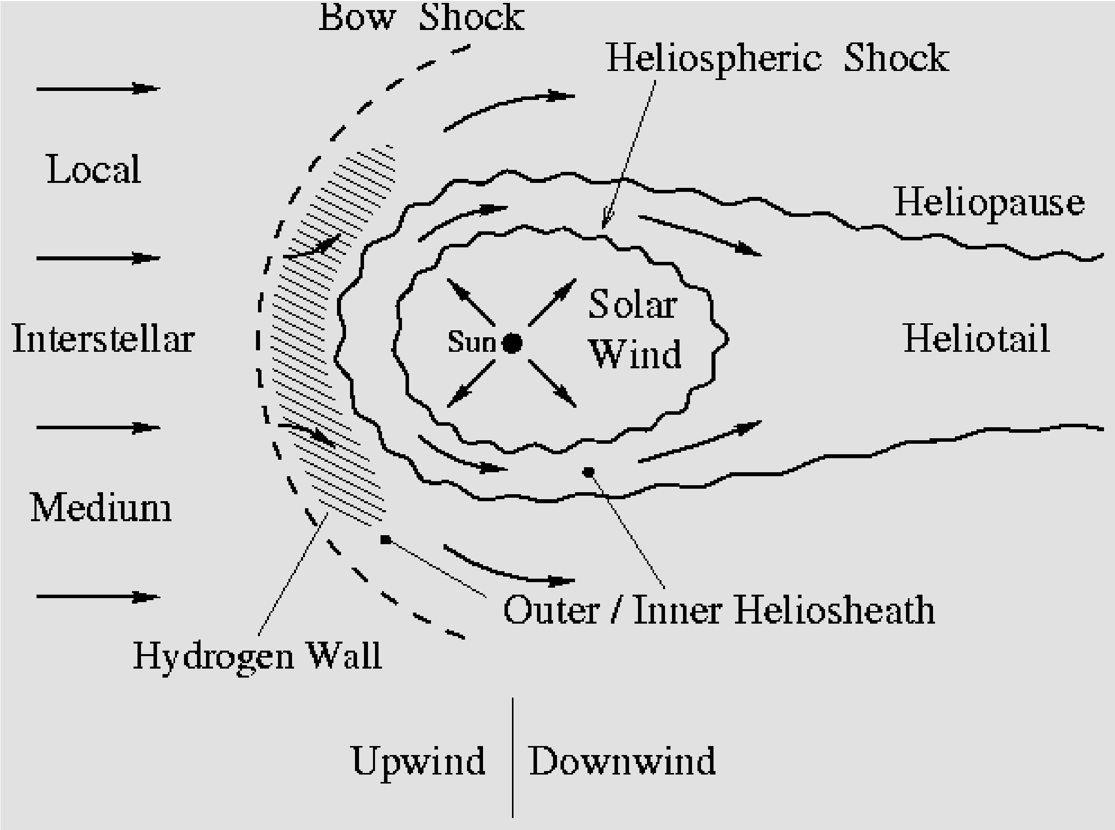
Heliosphere and local interstellar medium



(red) - 0.3 > $\log(n_e/cm^3)$ > - 3.7 (blue)

Kausch, 1998

Structure of the heliosphere

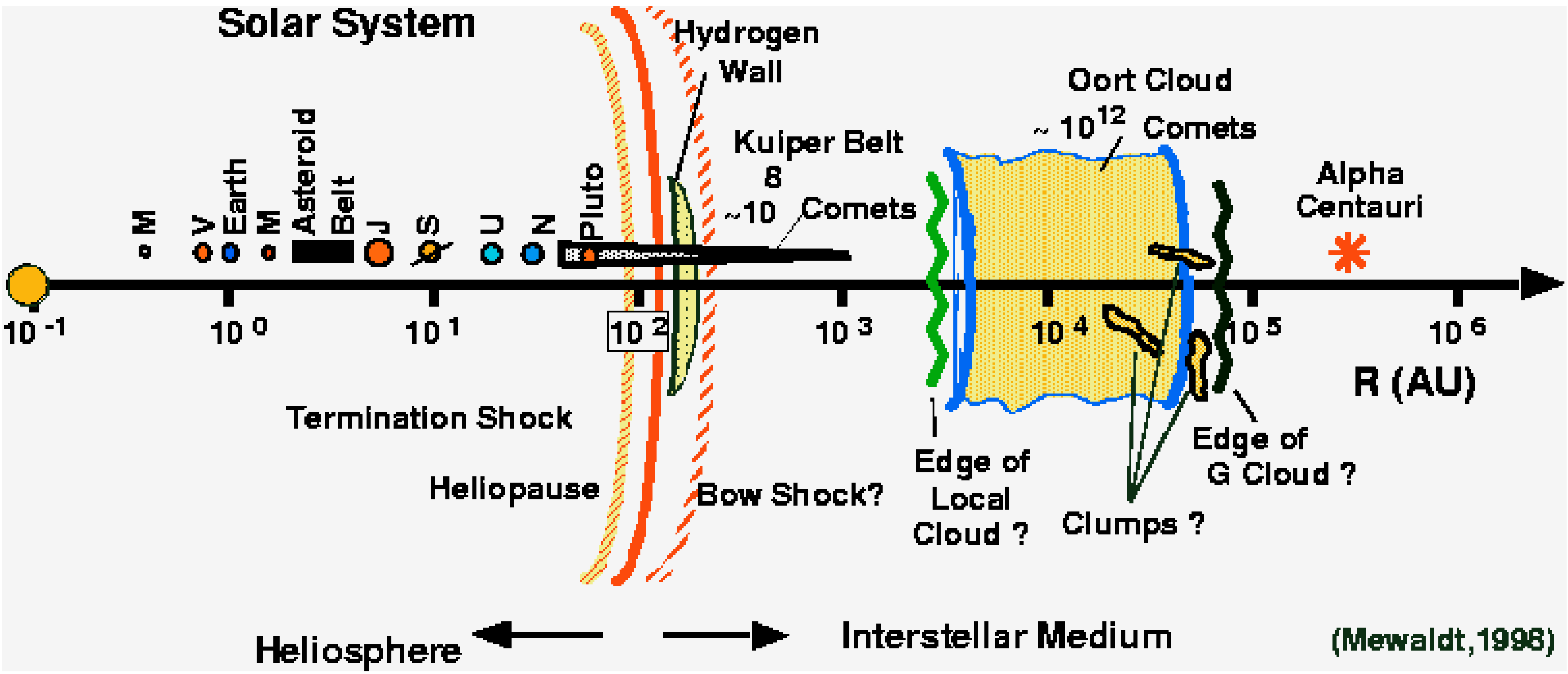


- **Basic plasma motions in the restframe of the Sun**
- **Principal surfaces (wavy lines indicate disturbances)**

Inventory of the heliosphere

- Interplanetary magnetic field (sun)
- Solar wind electrons and ions (corona)
- Solar energetic particles (solar atmosphere)
- Anomalous cosmic rays (planets, heliopause)
- Cosmic rays (galaxy)
- Pick-up ions (solar wind, dust, surfaces)
- Energetic neutrals (heliopause)
- Dust (interstaller medium, minor bodies)

The outer frontier



Termination schock at about 100 AU and Voyager at 80 AU

Length scales in the heliosphere

Macrostructure - fluid scales

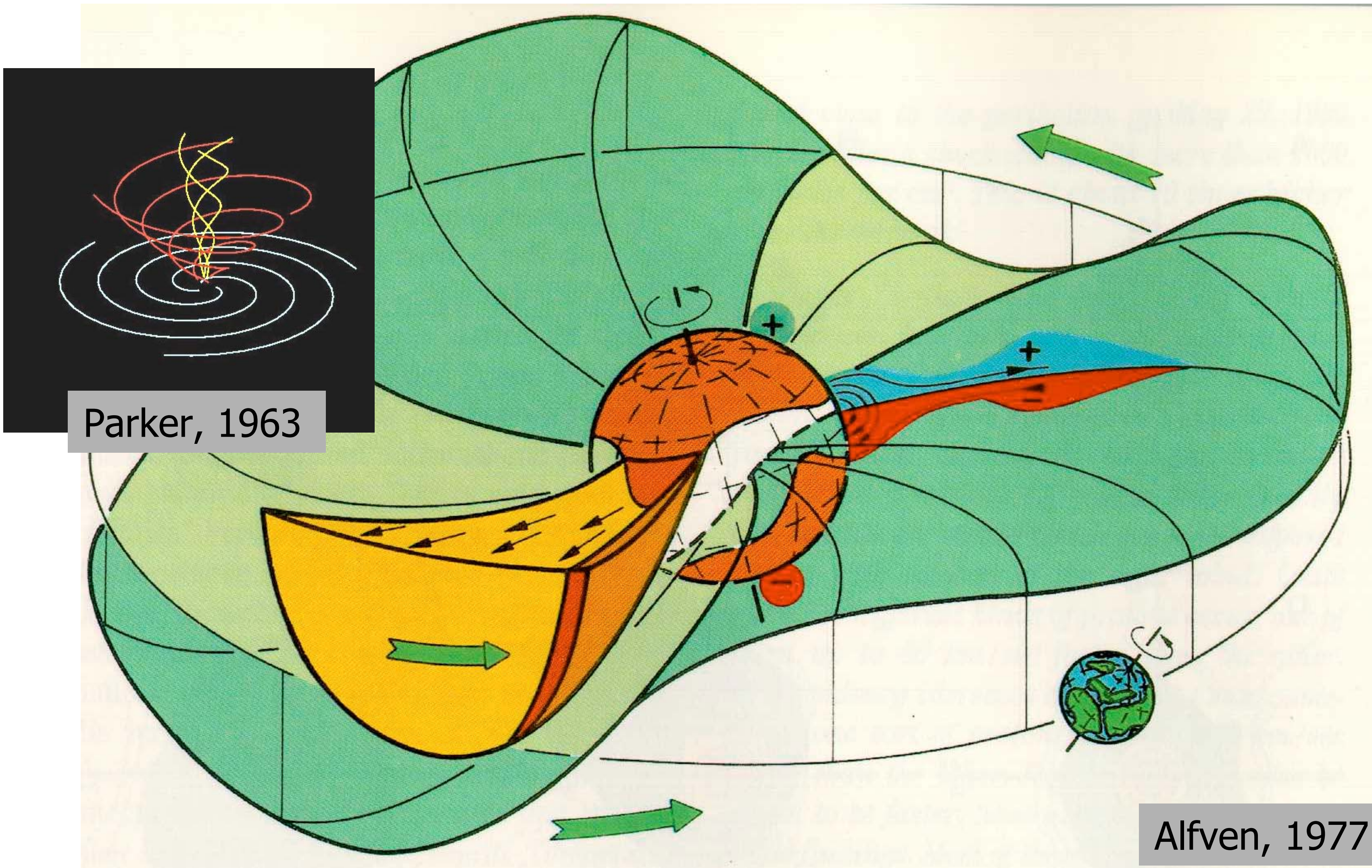
• Heliocentric distance:	r	150 Gm (1AU)
• Solar radius:	R_s	696000 km (215 R_s)
• Alfvén waves:	λ	30 - 100 Mm

Microstructure - kinetic scales

• Coulomb free path:	l	~ 0.1 - 10 AU
• Ion inertial length:	V_A/Ω_p (c/ω_p)	~ 100 km
• Ion gyroradius:	r_L	~ 50 km
• Debye length:	λ_D	~ 10 m
• Helios spacecraft:	d	~ 3 m

Microscales vary with solar distance!

Solar wind stream structure and heliospheric current sheet

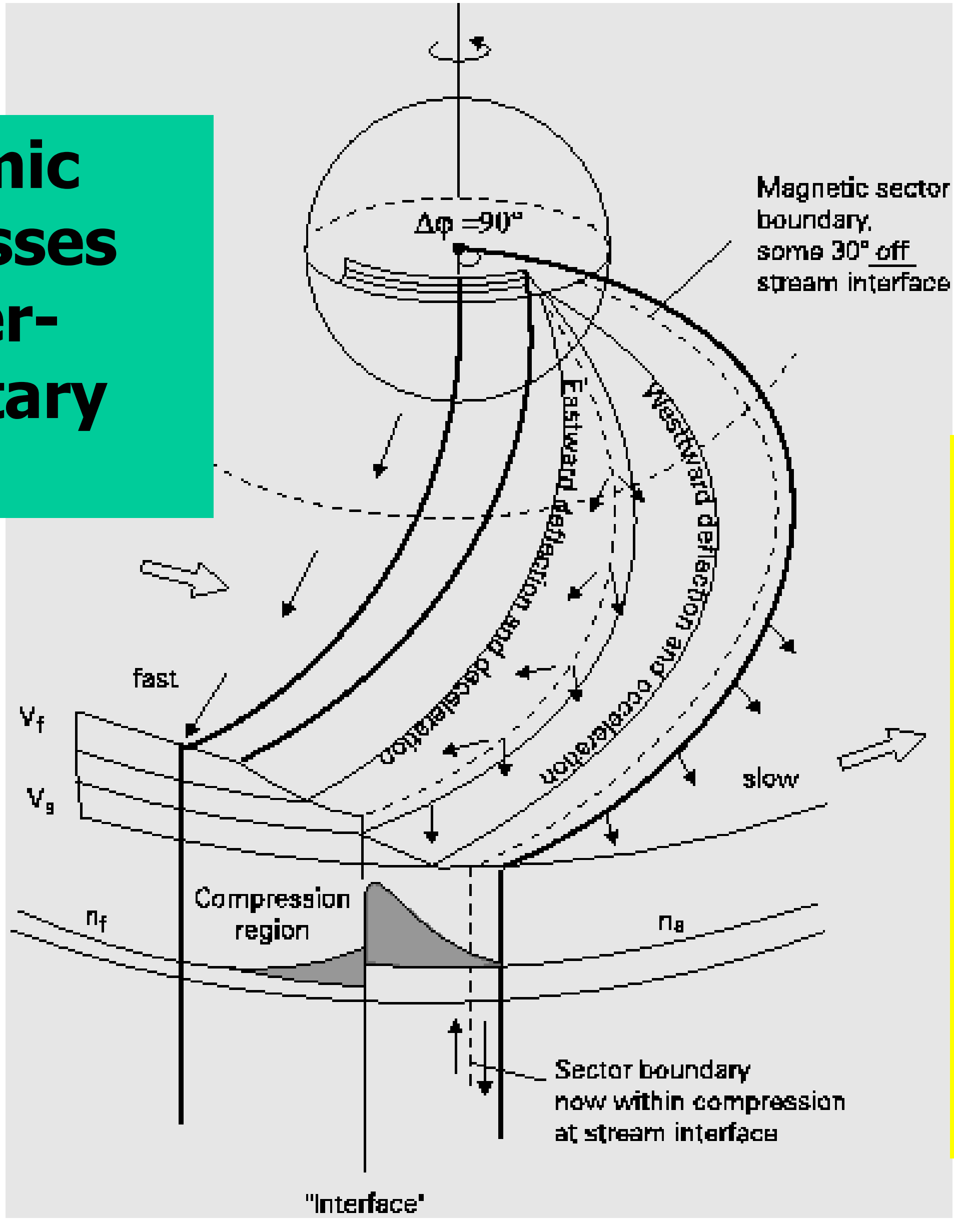


Parker, 1963

Alfven, 1977

Stream interaction region

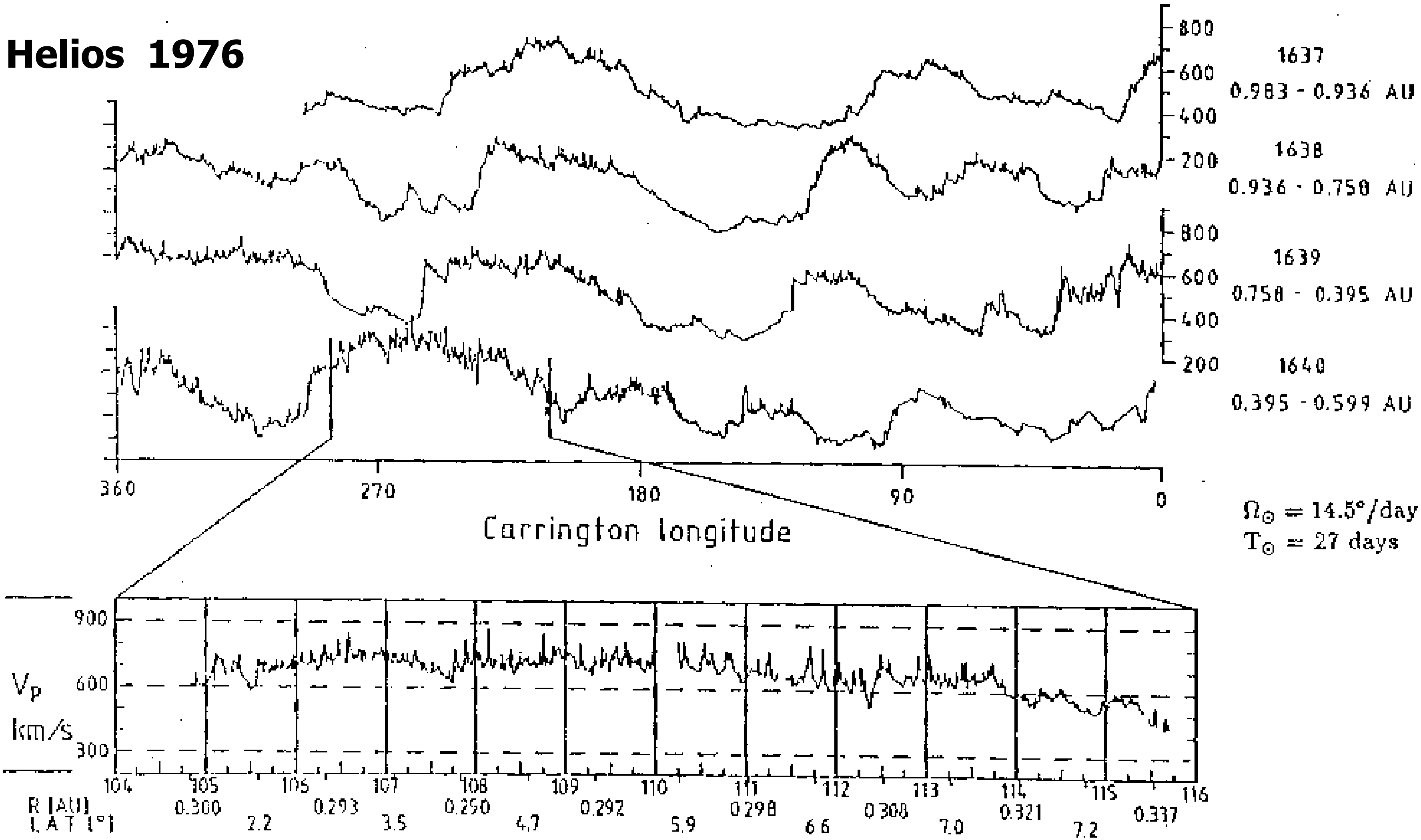
Dynamic processes in inter-planetary space



- **Wave amplitude steepening ($n \sim r^{-2}$)**
- **Compression and rarefaction**
- **Velocity shear**
- **Nonlinearity by advection $(\underline{V} \bullet \underline{\nabla})\underline{V}$**
- **Shock formation (co-rotating)**

Solar wind fast and slow streams

Helios 1976



Alfvén waves and small-scale structures

Marsch, 1991

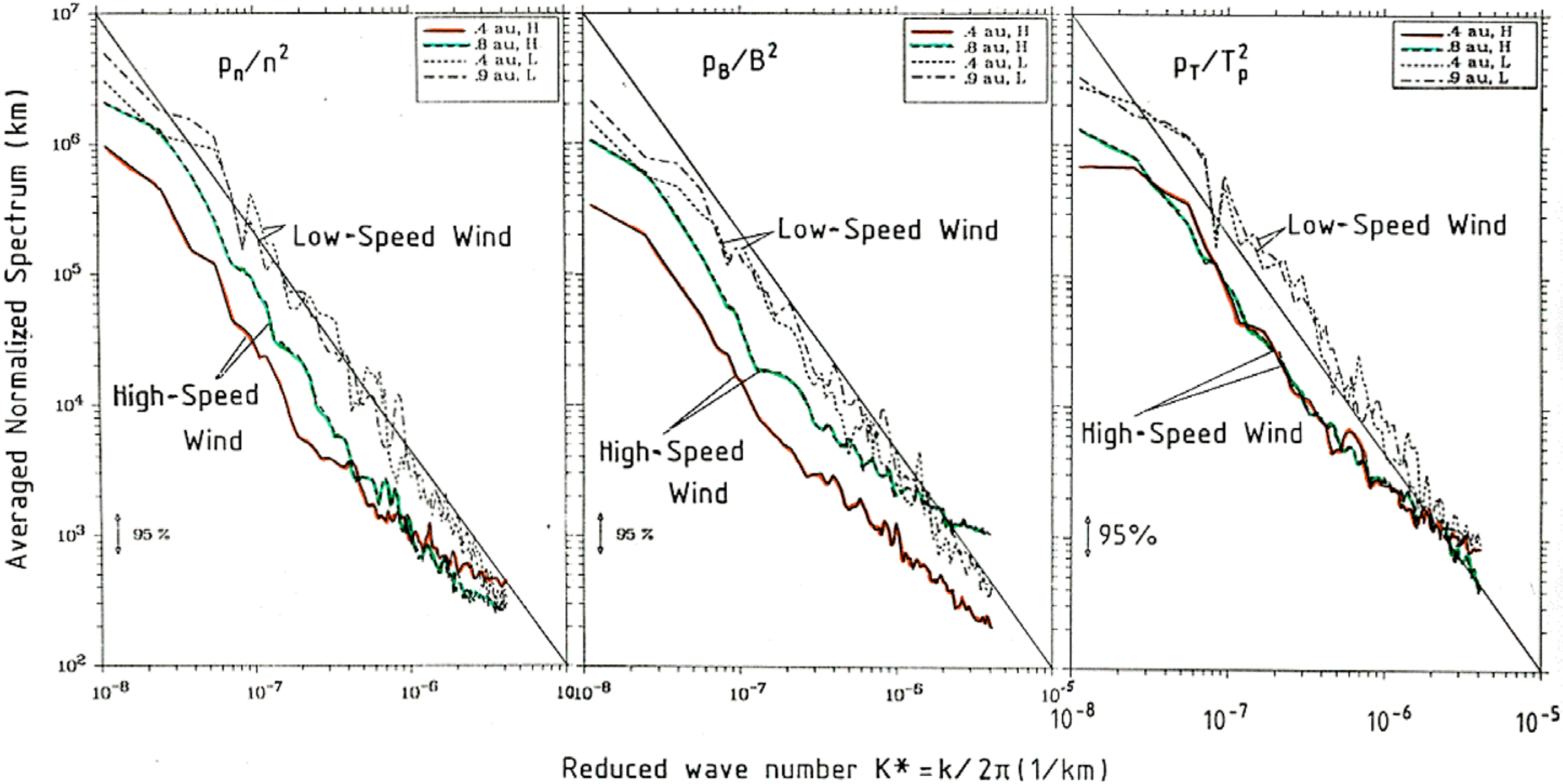
Spatial and temporal scales

Phenomenon	Frequency (s^{-1})	Period (day)	Speed (km/s)
Solar rotation:	$4.6\ 10^{-7}$	25	2
Solar wind expansion:	$5 - 2\ 10^{-6}$	2 - 6	800 - 250
Alfvén waves:	$3\ 10^{-4}$	1/24	50 (1AU)
Ion-cyclotron waves:	1 - 0.1	1 (s)	(V_A) 50

Turbulent cascade: generation + transport

→ inertial range → kinetic range + dissipation

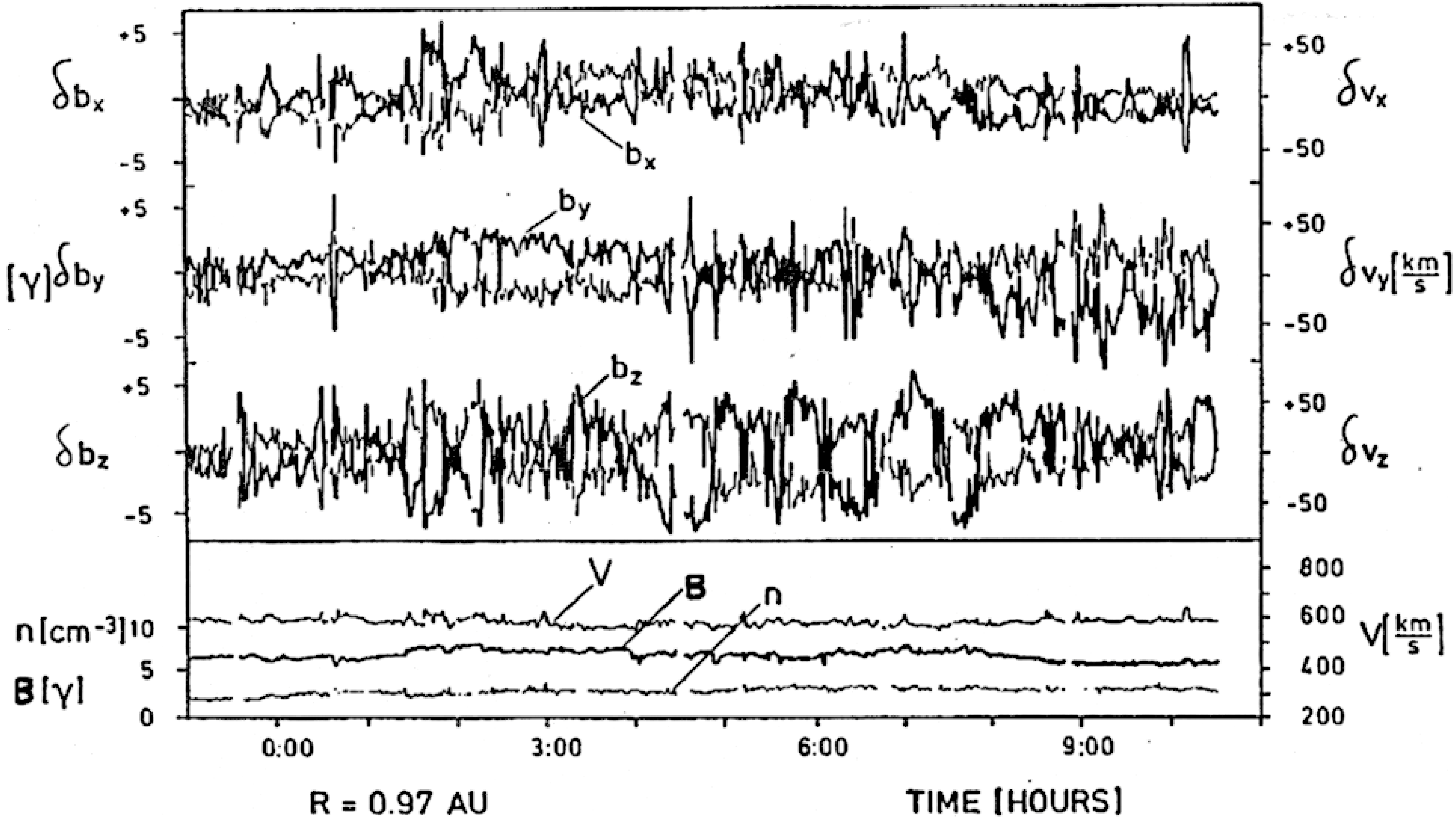
Compressive fluctuations in the solar wind



Marsch and Tu, JGR, **95**, 8211, 1990

Kolmogorov-type turbulence

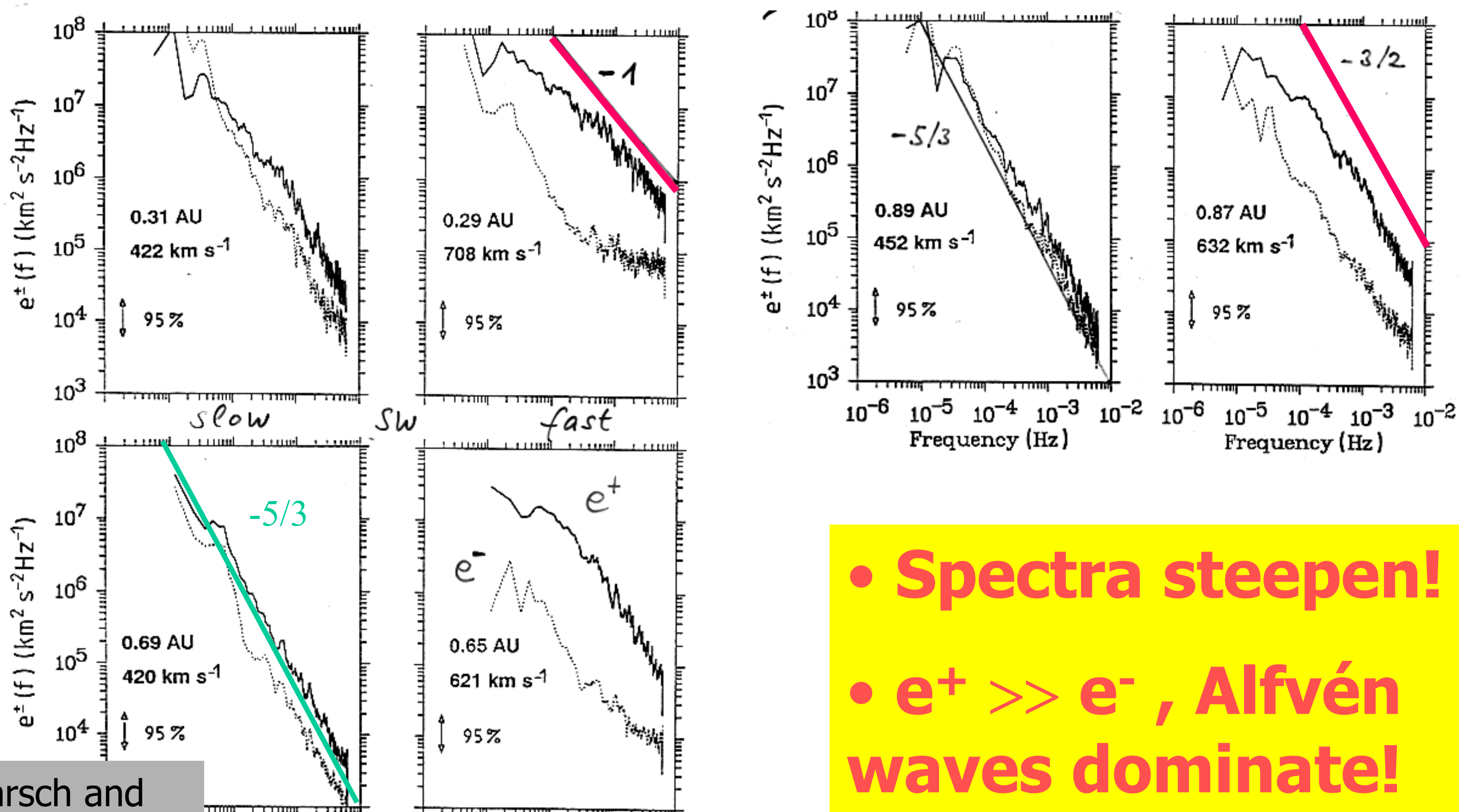
Alfvénic fluctuations



Neubauer et al., 1977

$\delta \mathbf{V} = \pm\, \delta \mathbf{V}_A$

Spectral indices and spatial evolution of turbulence



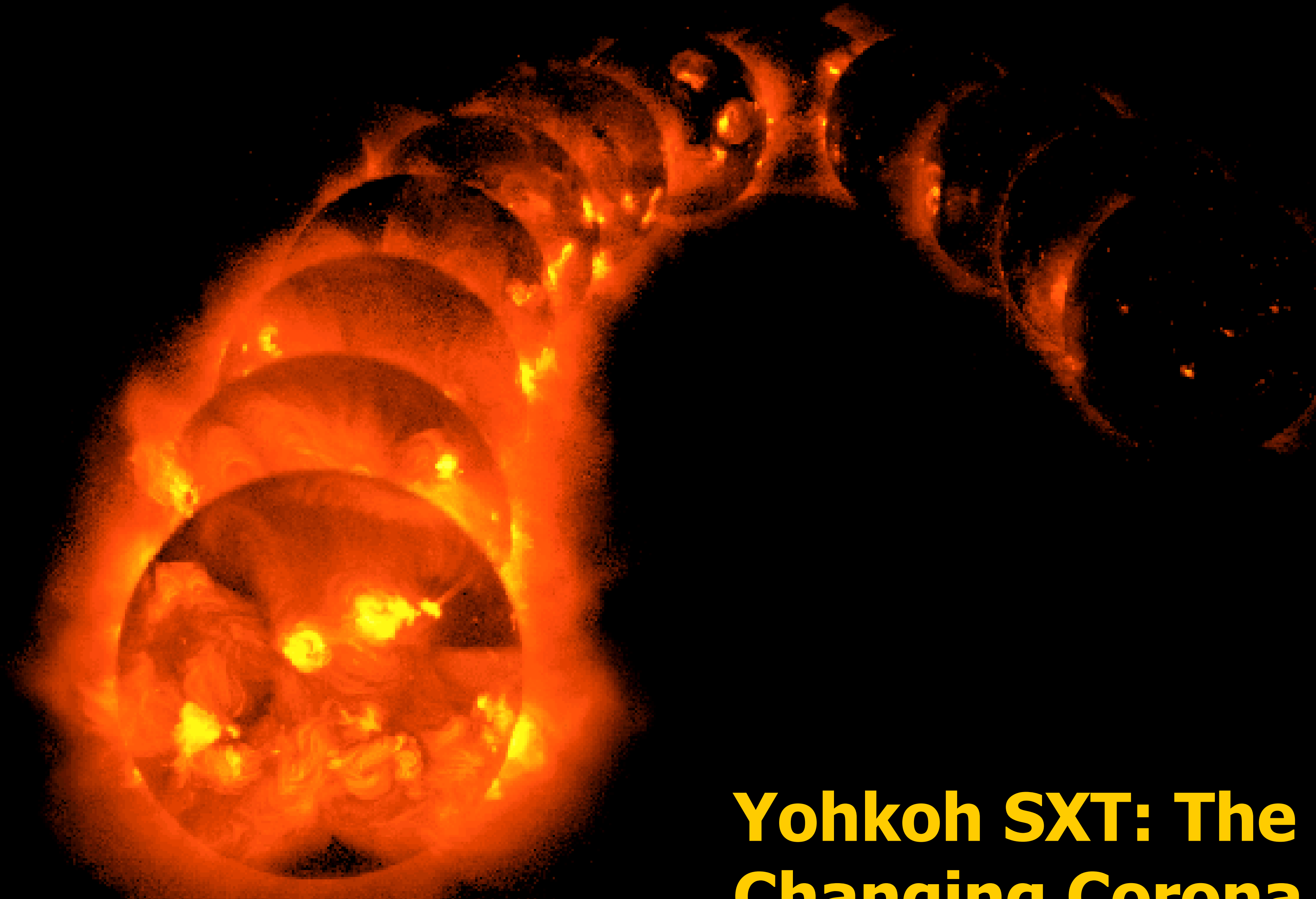
- **Spectra steepen!**
- **$e^+ \gg e^-$, Alfvén waves dominate!**

Marsch and Tu, JGR, **95**, 8211, 1990

slow <-> fast wind

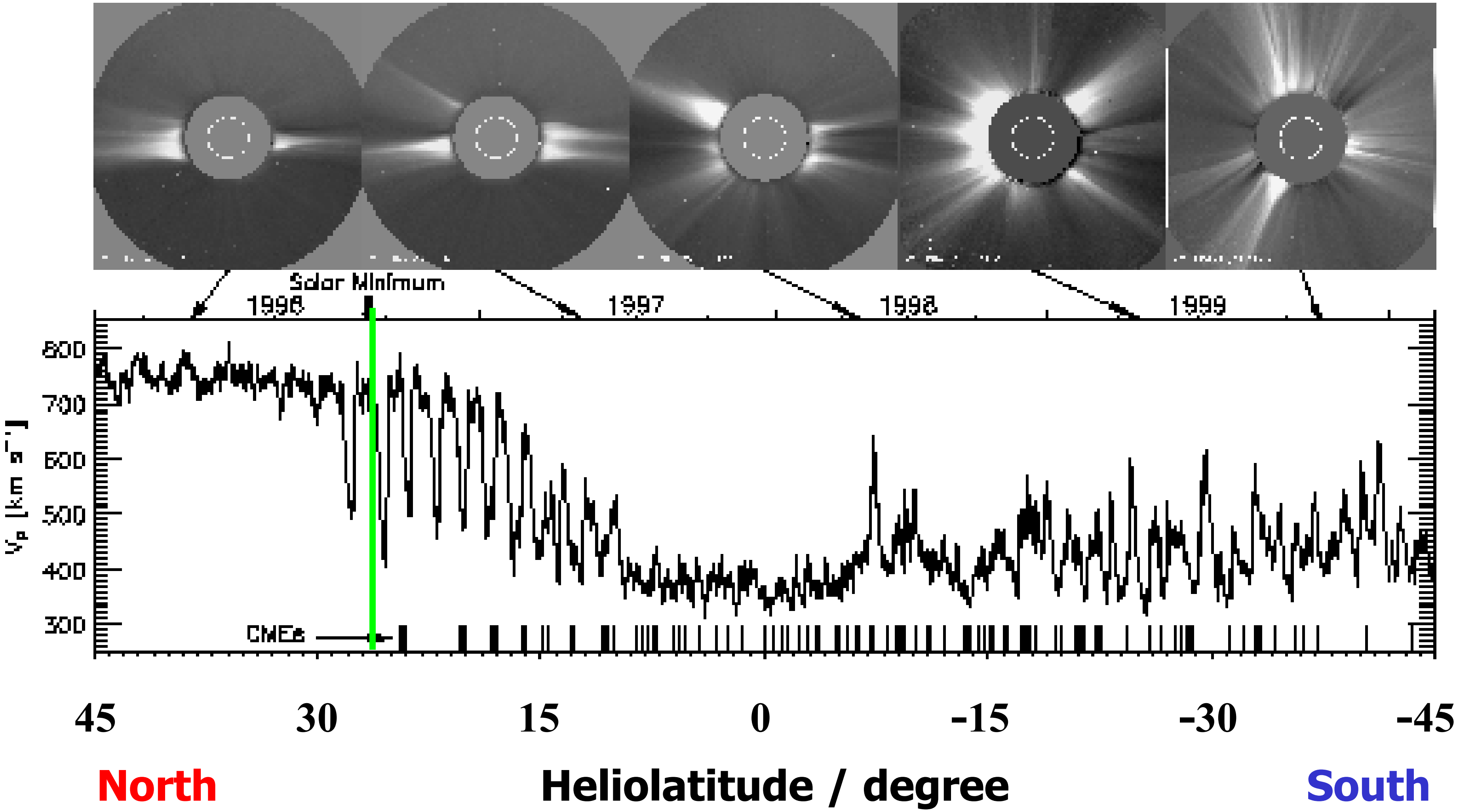
Solar wind turbulence

Parameter	Coronal Hole (open)	Current sheet (closed)
Alfvén waves:	yes	no
Density fluctuations:	weak (<3%)	intense (>10%)
Magnetic/kinetic turbulent energy:	$\cong$ 1	> 1
Spectral slope:	flat (-1)	steep (-5/3)
Wind speed:	high	low
T_p (T_e):	high (low)	low (high)
Wave heating:	strong	weak



Yohkoh SXT: The Changing Corona

Changing corona and solar wind

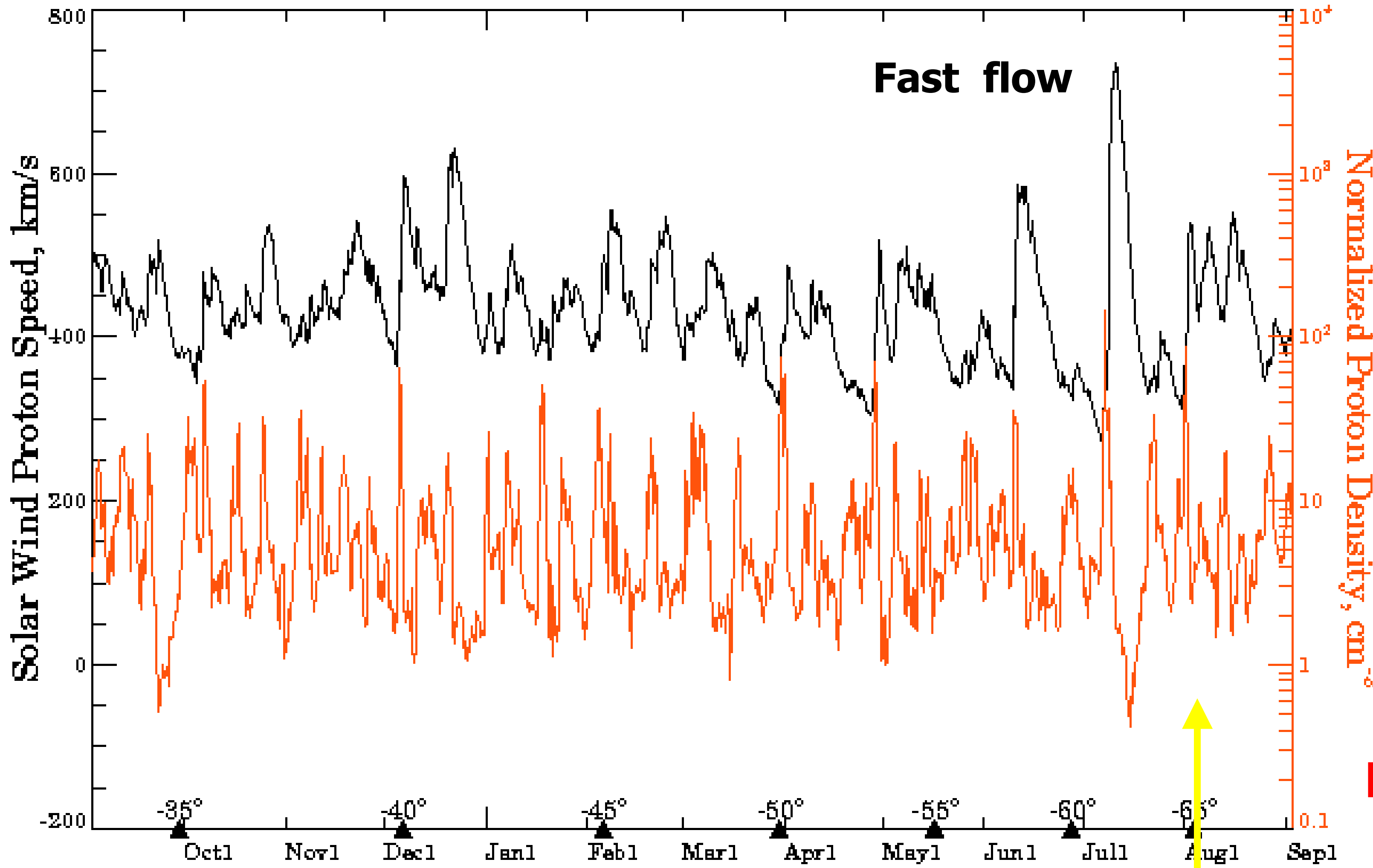


McComas et al., 2000

LASCO/Ulysses

New solar wind data from Ulysses

V

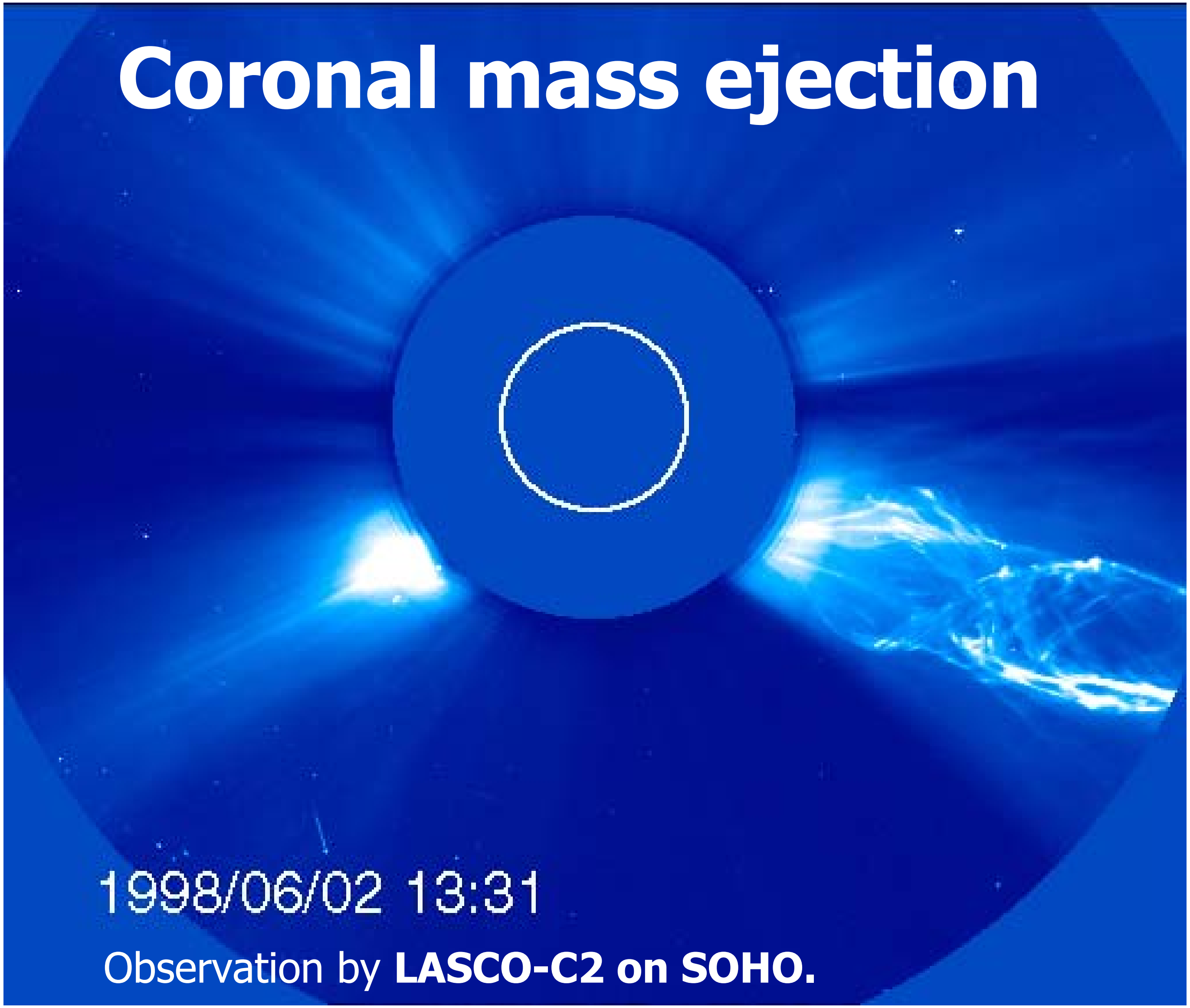


n

McComas et al., 2000

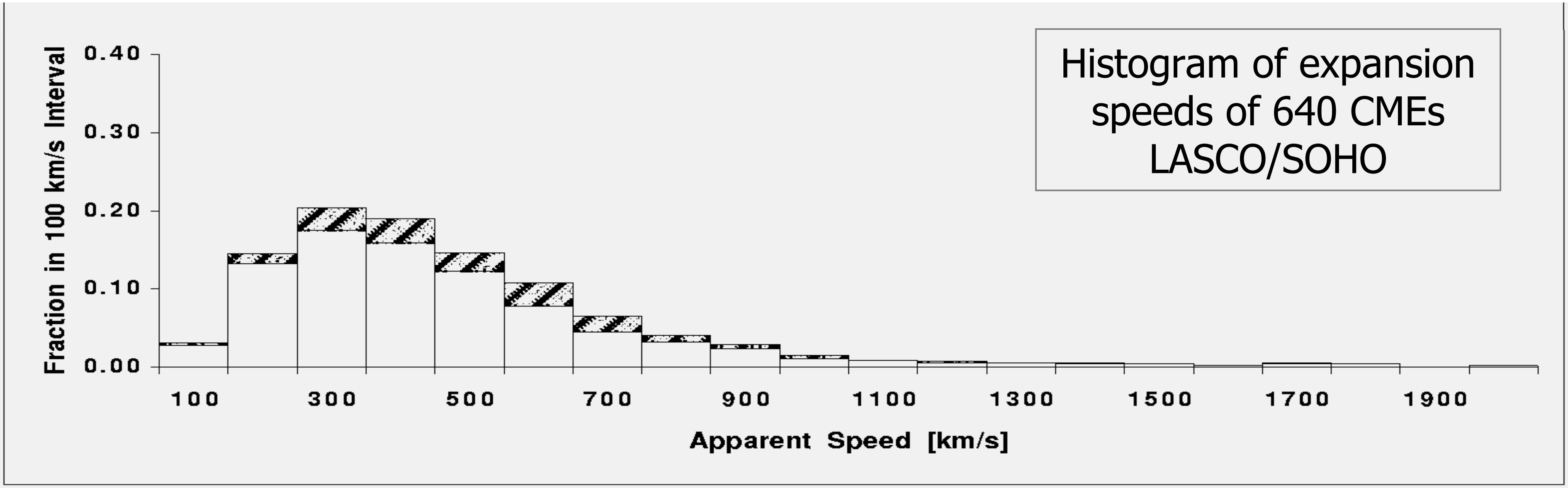
September 3, 1999 - September 2, 2000

Latitude: - 65°



Note the helical structure of the prominence filaments!

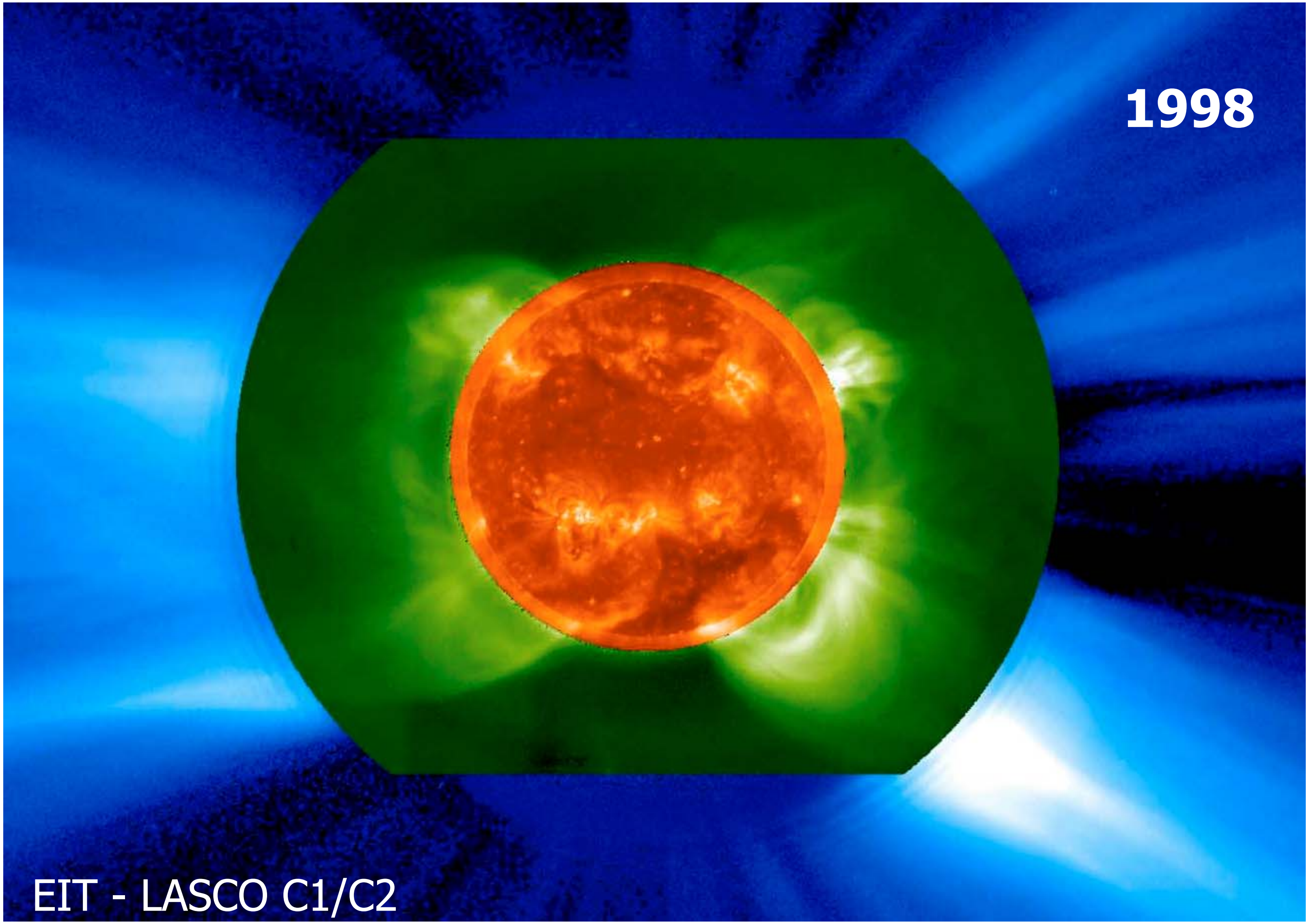
Speeds of CMEs (1996 to 1998)



- Flare-associated fast CMEs with 0.3 ms^{-2} and initial V > 700 km/s
- Eruptive slow CMEs with 0-50 ms^{-2} and initial V = 10-20 km/s

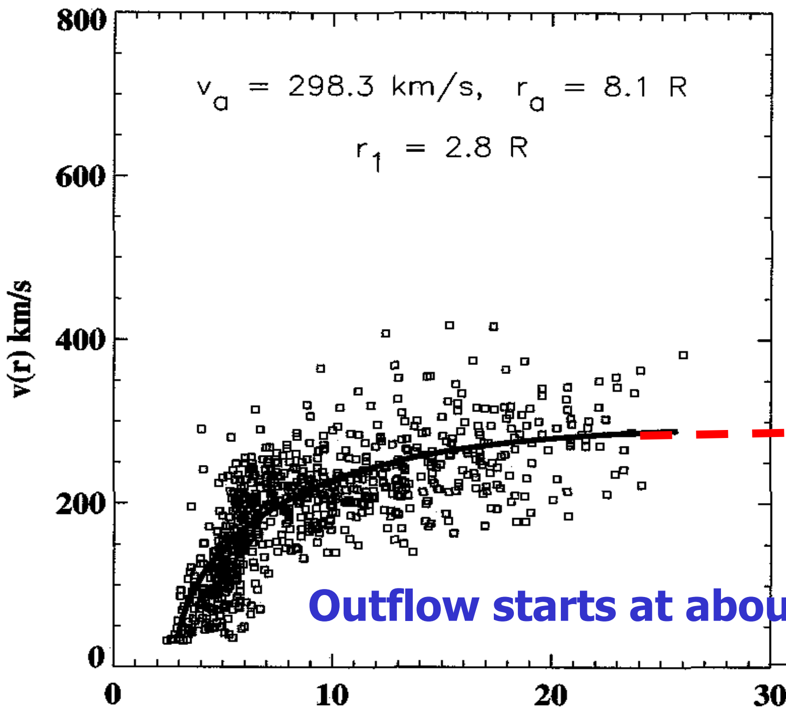
St.Cyr et al., 2000

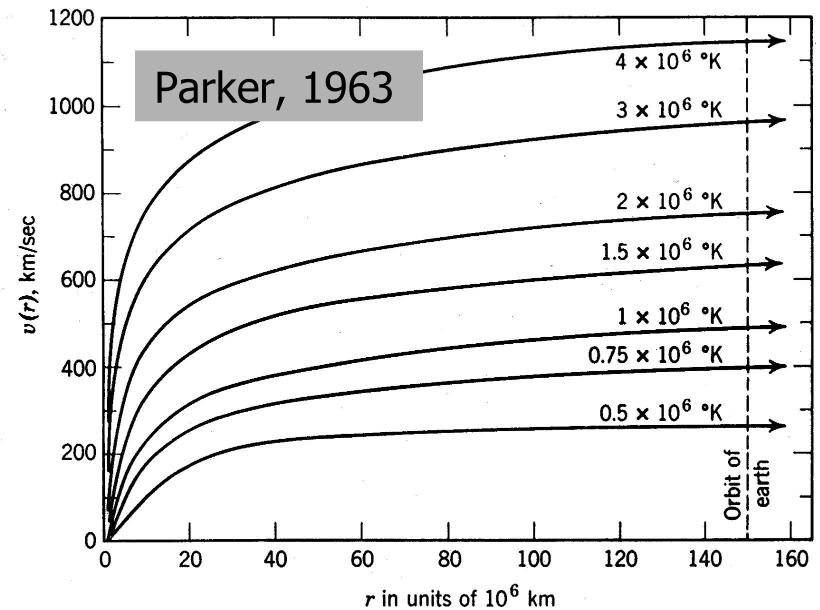
Corona of the active sun



Speed profile of the slow solar wind

Speed profile as determined from plasma blobs in the wind





Outflow starts at about 3 R_S

Radial distance / R_S **60**

Sheeley et al., Ap.J., **484**, 472, 1998

Consistent with Helios data

North coronal hole in various lines

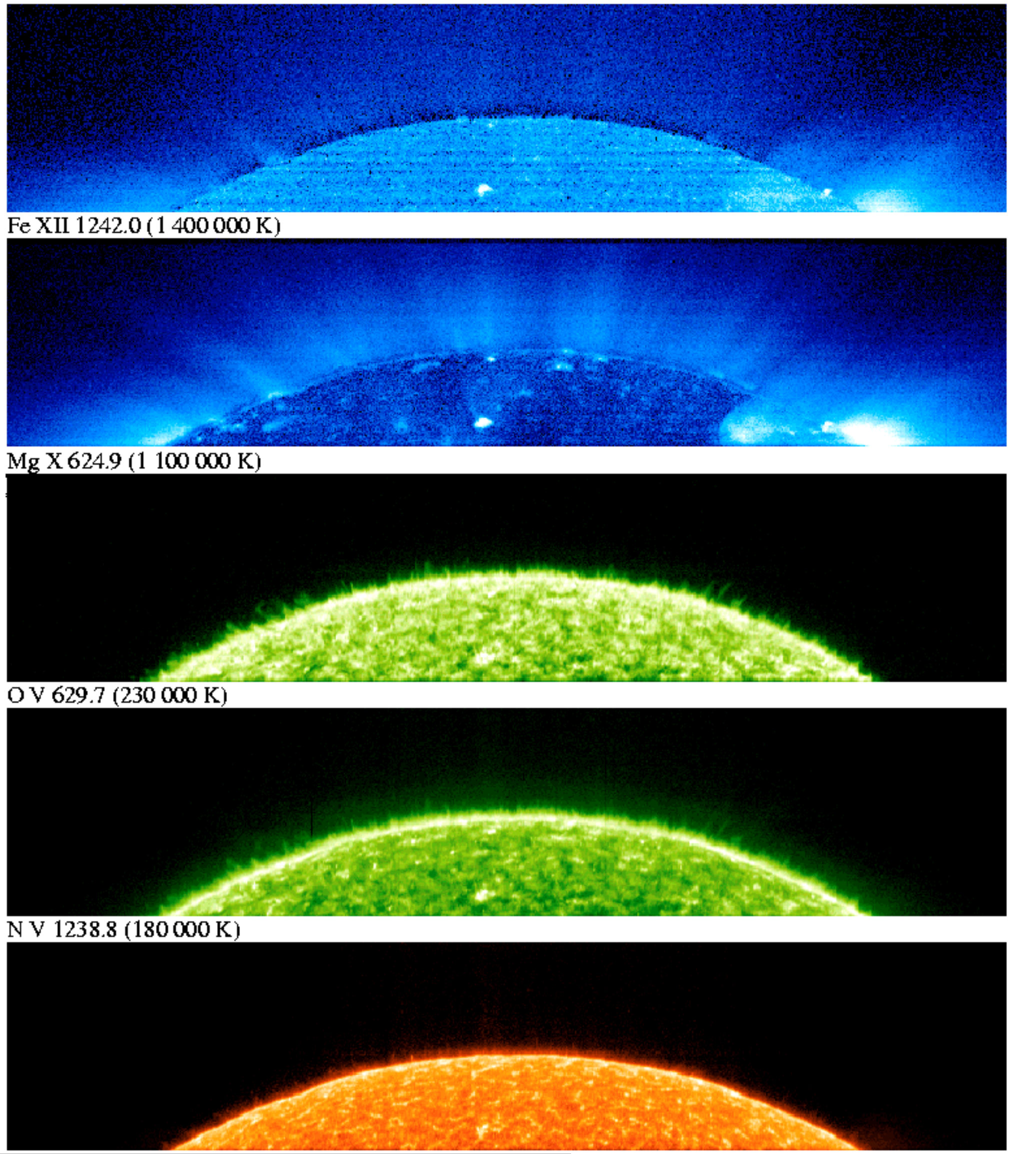
1400000 K — FeXII 1242 Å

1100000 K — MgX 624.9 Å

230000 K — OV 629.7 Å

180000 K — NV 1238.8 Å

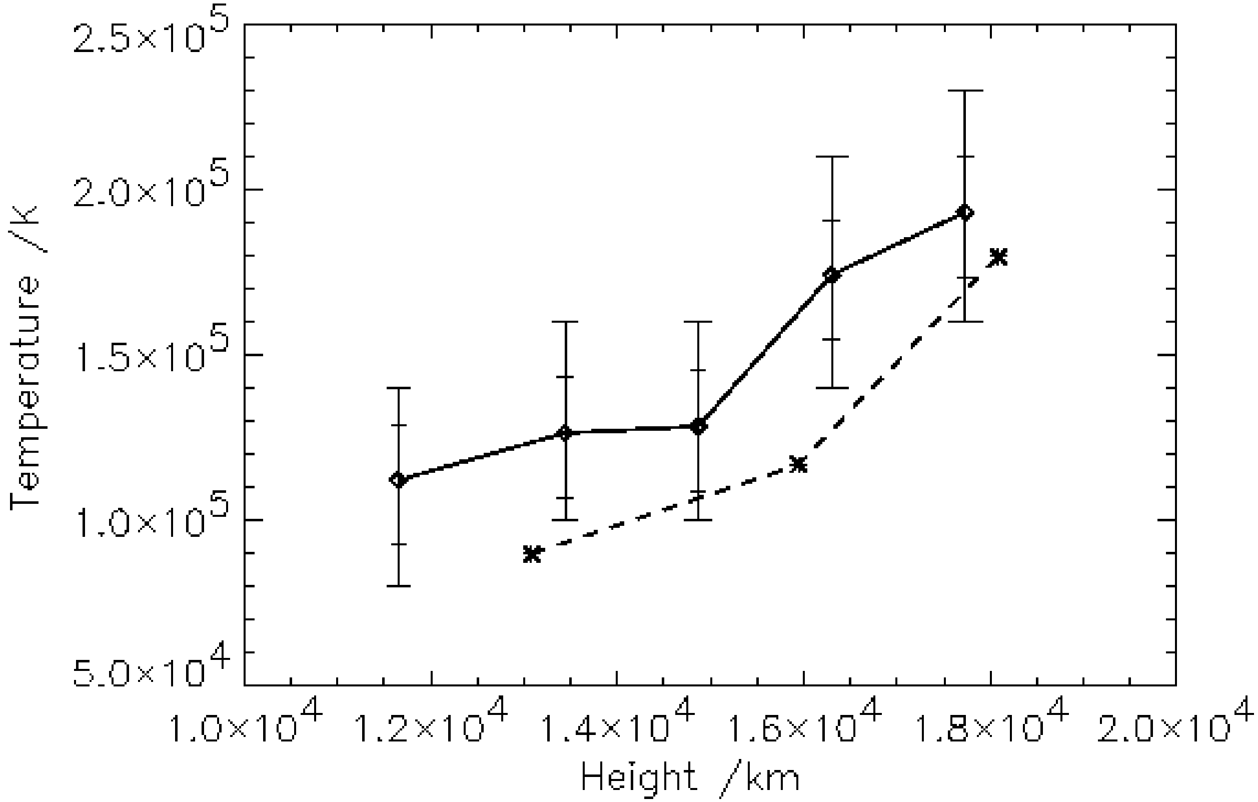
10000 K — cont. 1240 Å



Forsyth & Marsch, Space Sci. Rev., **89**, 7, 1999

SUMER/SOHO 10 August 1996

Proton temperature at coronal base



SUMER/SOHO

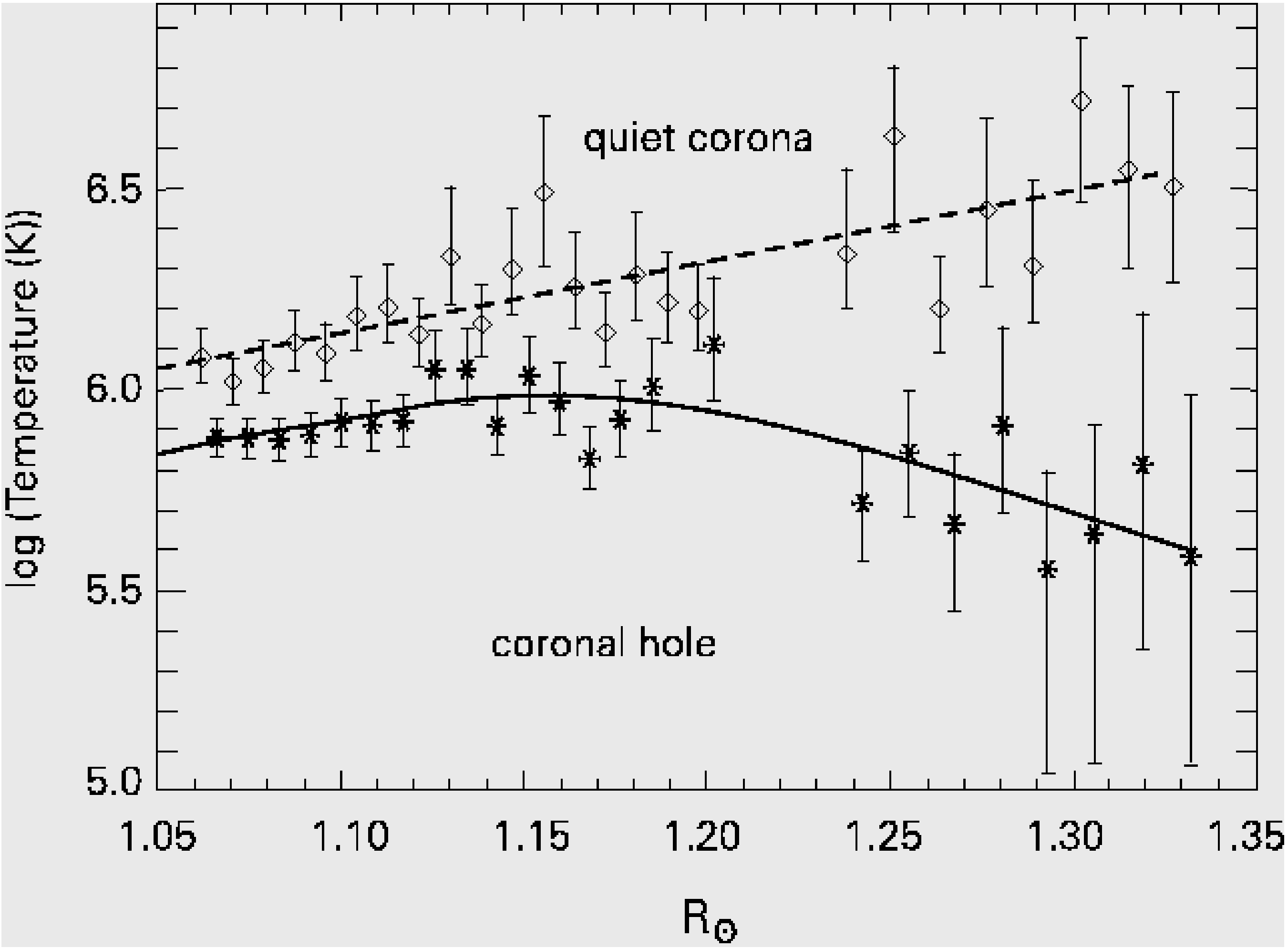
Hydrogen Lyman series

Transition Region at the base of north polar CH

Marsch et al., A&A, in press, 2000

Charge-exchange equilibrium: $T_H = T_p$
Turbulence broadening: $\xi = 30$ km s^{-1}

Electron temperature in the corona



Streamer belt, closed

Coronal hole, open magnetically

David et al., A&A, **336**, L90, 1998

Heliocentric distance

SUMER/CDS SOHO

Heavy ion heating proportional to charge/mass by cyclotron resonance

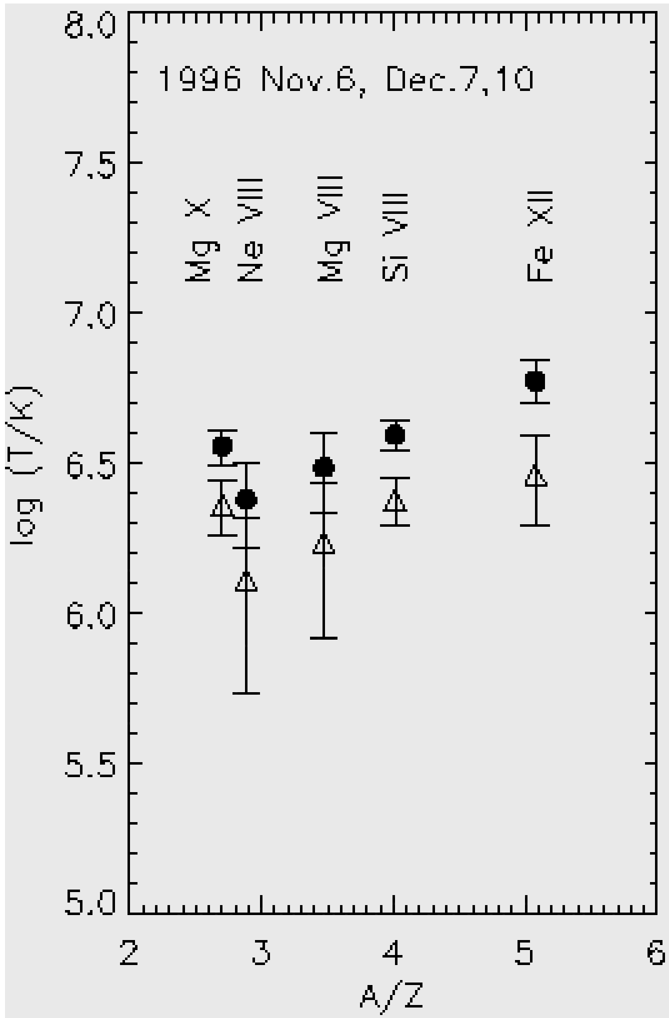
$\Omega \sim Z/A$

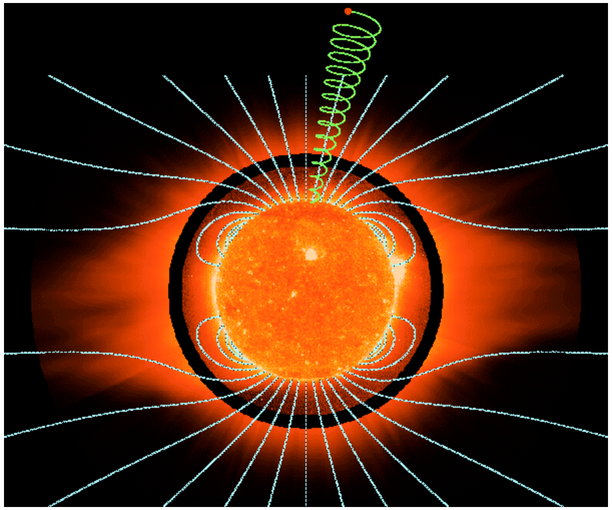
Heavy ion temperature

T=(2-6) MK

r = 1.15 R_S

Tu et al., Space Sci. Rev., **87**, 331, 1999

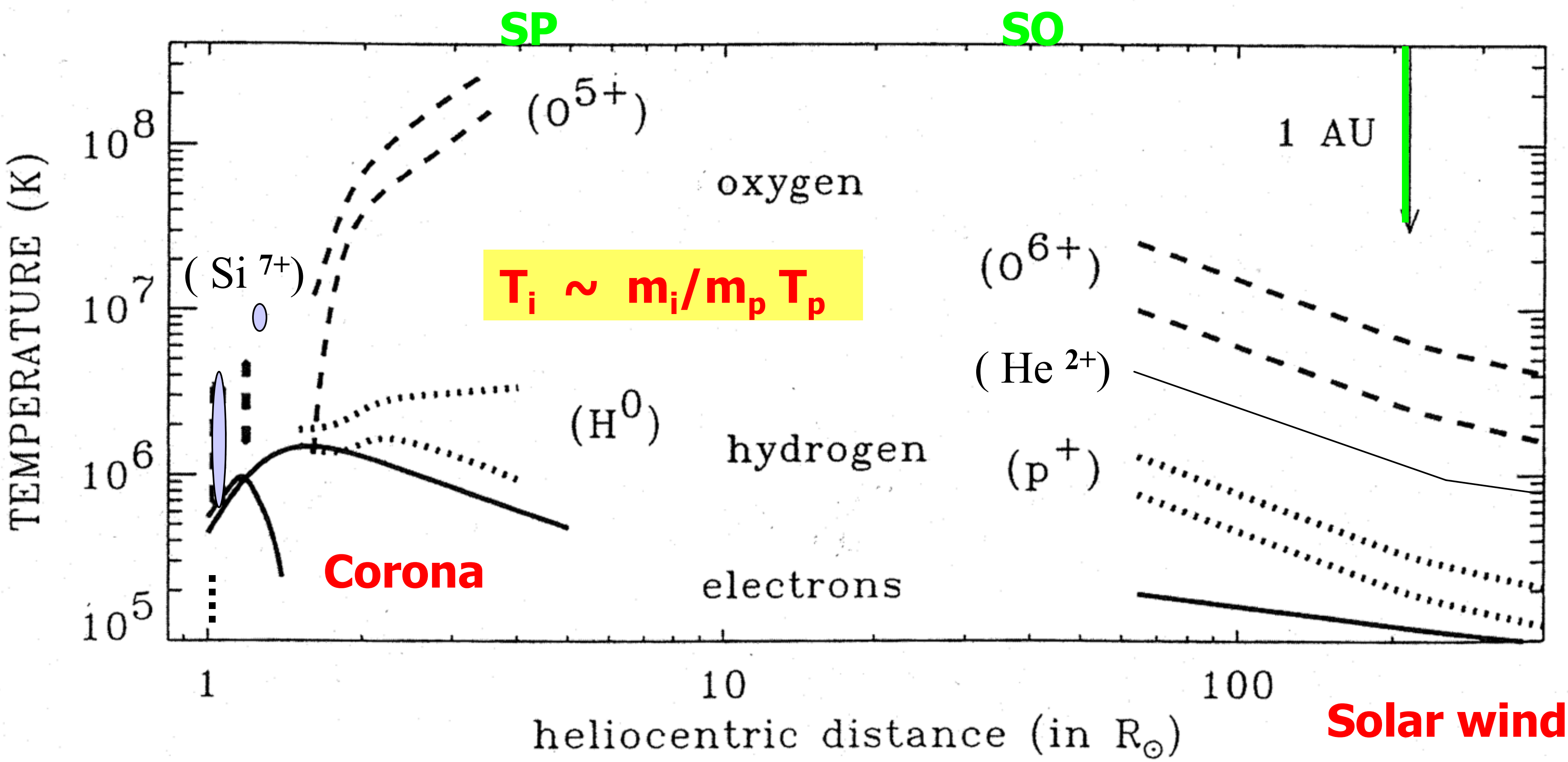




• Magnetic mirror in coronal funnel/hole
• Cyclotron resonance
$\Rightarrow$ increase of μ

SUMER/SOHO

Temperature profiles in the corona and fast solar wind

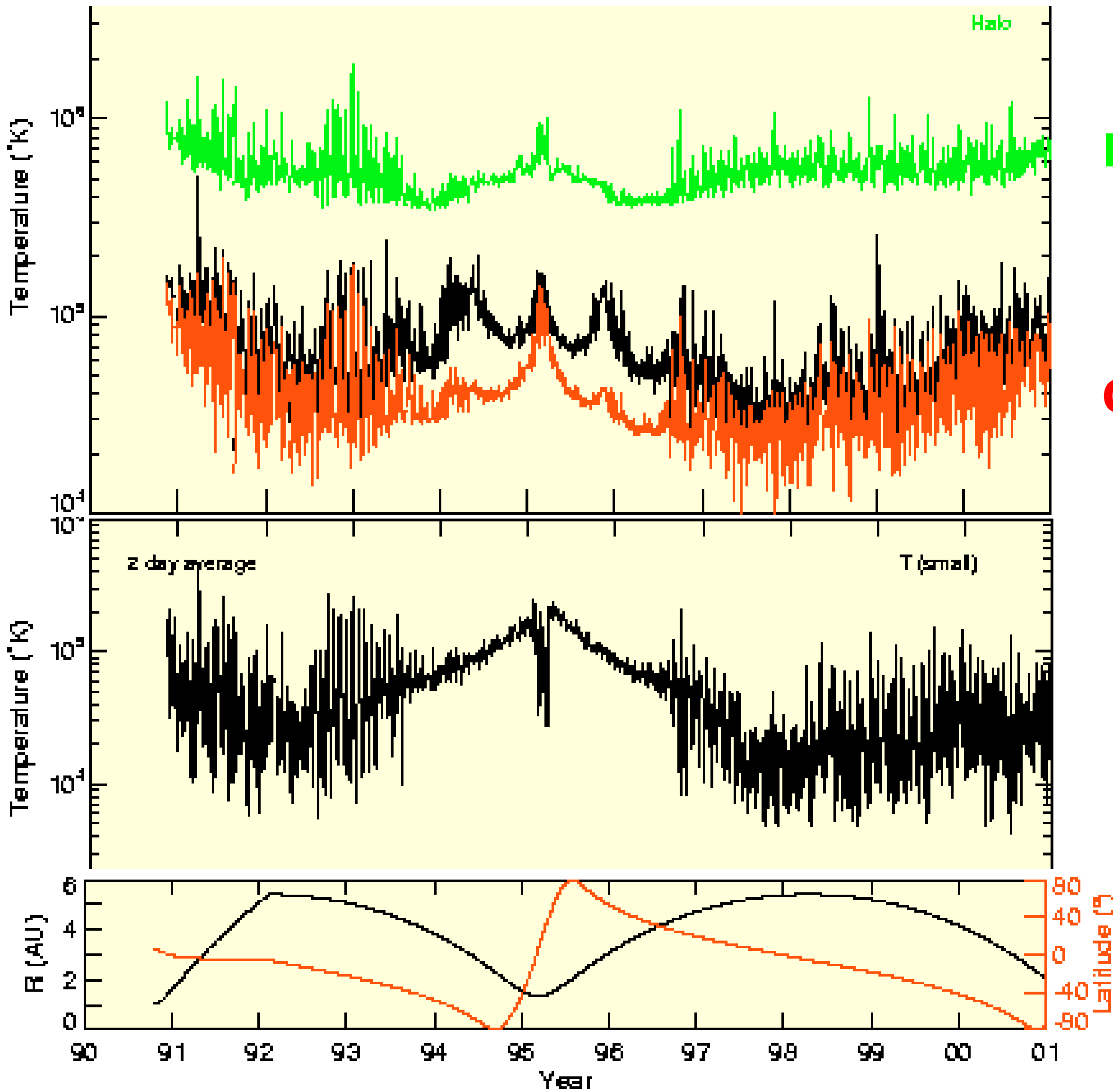


Cranmer et al., Ap.J., 2000; Marsch, 1991

Heliospheric temperatures

Electrons

Protons



Halo (4%)

Core (96%)

$T_p \leq T_e$

Ulysses

McComas et al., 1998

Theoretical description

Boltzmann-Vlasov kinetic equations for protons, alpha-particles (4%), minor ions and electrons

↙ ↘

Distribution functions

Moments

Kinetic equations

+ Coulomb collisions (Landau)
+ Wave-particle interactions
+ Micro-instabilities (Quasilinear)
+ Boundary conditions

→ **Particle velocity distributions and field power spectra**

Multi-Fluid (MHD) equations

+ Collision terms
+ Wave (bulk) forces
+ Energy addition
+ Boundary conditions

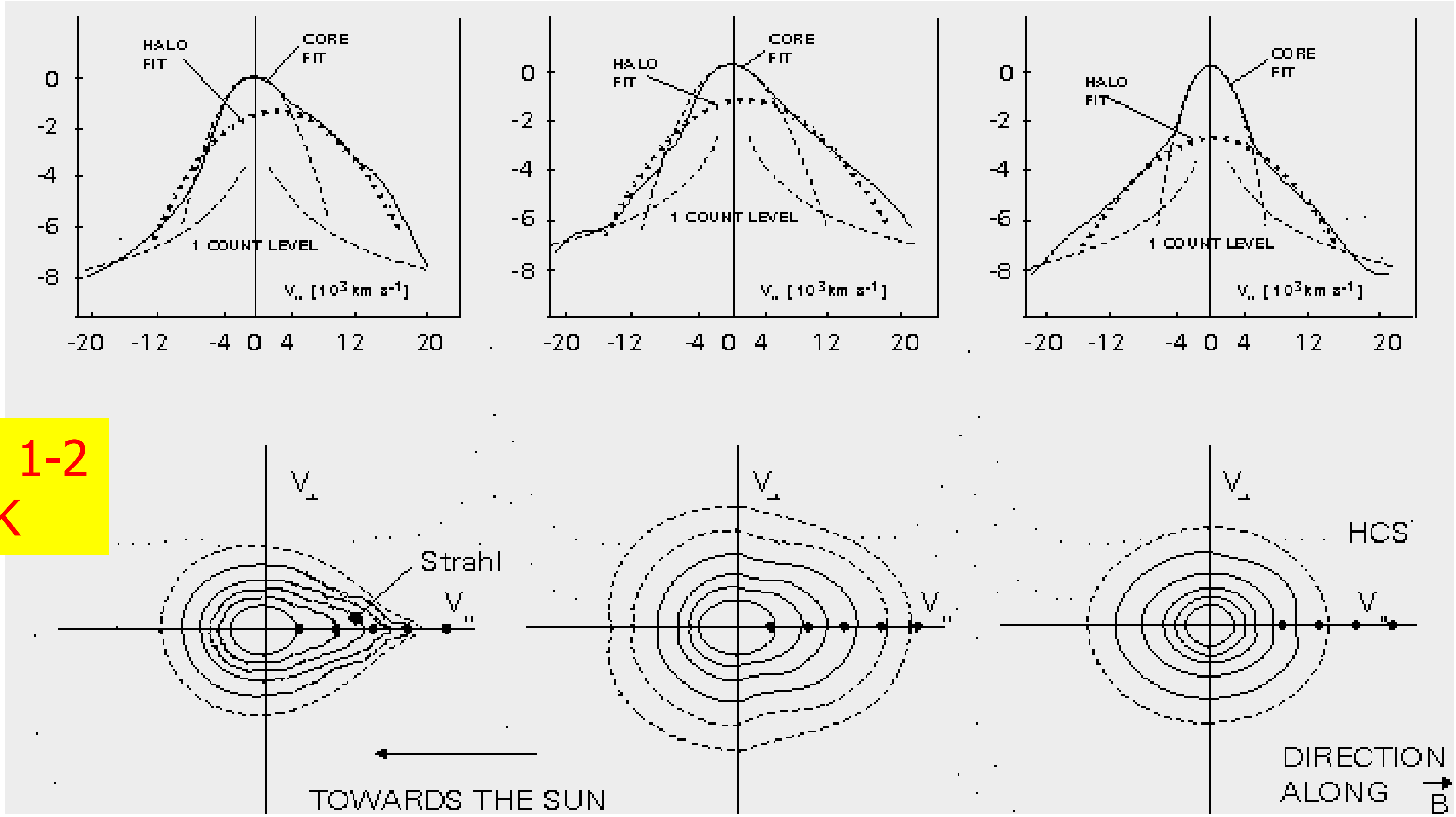
→ **Single/multi fluid parameters**

Coulomb collisions

Parameter	Chromo -sphere	Corona ($1R_S$)	Solar wind (1AU)
n_e (cm^{-3})	10^{10}	10^7	10
T_e (K)	10^3	1-2 10^6	10^5
λ (km)	10	1000	10^7

- Since $N < 1$, Coulomb collisions require kinetic treatment!
- Yet, only a few collisions ($N \geq 1$) remove extreme anisotropies!
- Slow wind: $N > 5$ about 10%, $N > 1$ about 30-40% of the time.

Electron velocity distributions



T_e = 1-2 10^5 K

high intermediate speed low

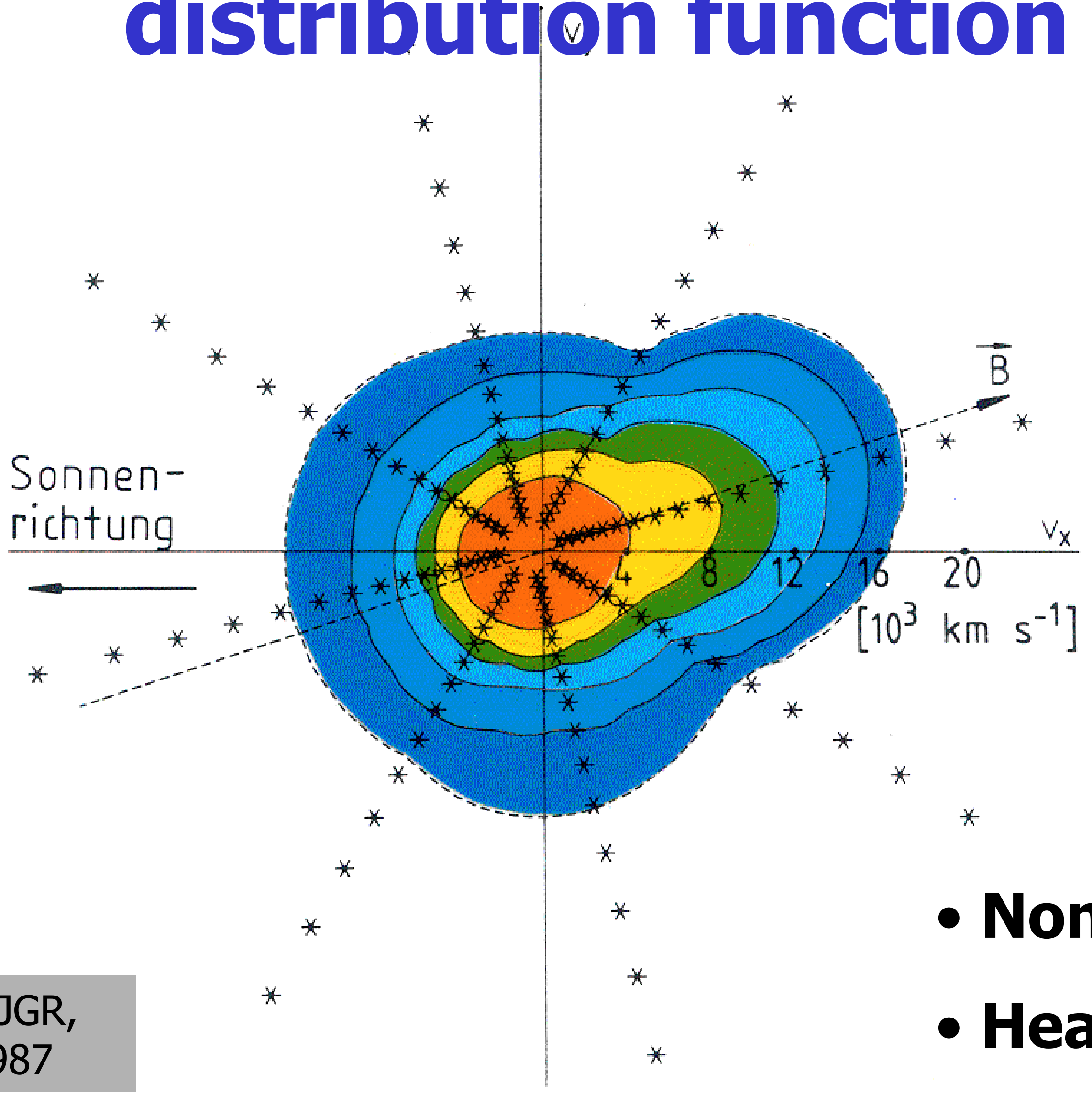
Pilipp et al., JGR, **92**, 1075, 1987

Core (96%), halo (4%) electrons, and „strahl“

Electron velocity distribution function

Helios

Sun



$n_e = 3\text{-}10\ cm^{-3}$

- **Non-Maxwellian**
- **Heat flux tail**

Pilipp et al., JGR, **92**, 1075, 1987

Electron heat conduction

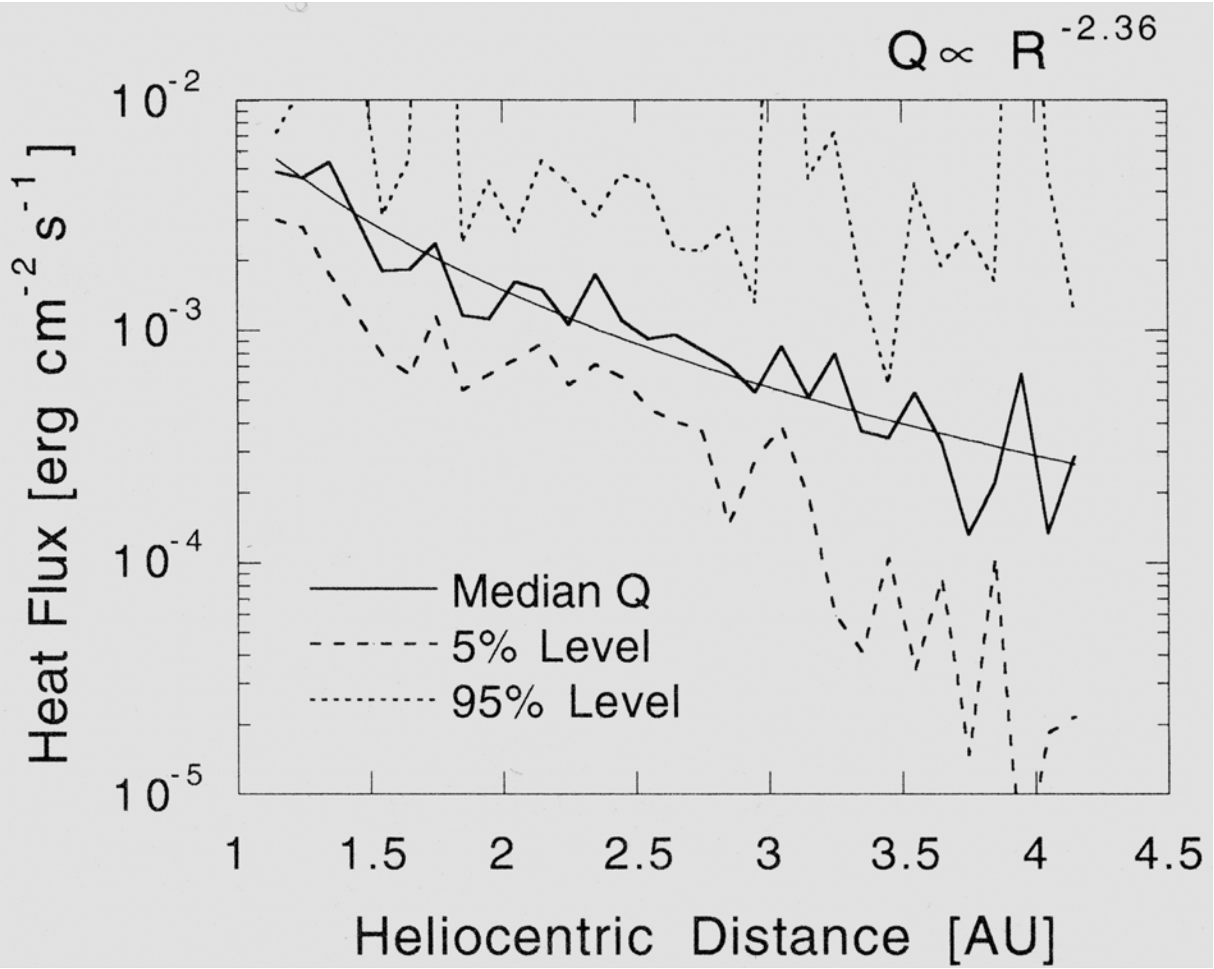
Heat carried by halo electrons!

$T_H = 7\ T_C$

Interplanetary potential:

Φ **=** 50-100 eV

$\underline{\mathbf{E}} = -\,1/n_e\,\underline{\nabla}\,p_e$



$\underline{Q_e} \neq -\,\kappa\underline{\nabla}\,T_e$

McComas et al., GRL, **19**, 1291, 1992

Kinetic processes in the solar corona and solar wind

- Plasma is multi-component and nonuniform

$\rightarrow$ **complexity**

- Plasma is dilute

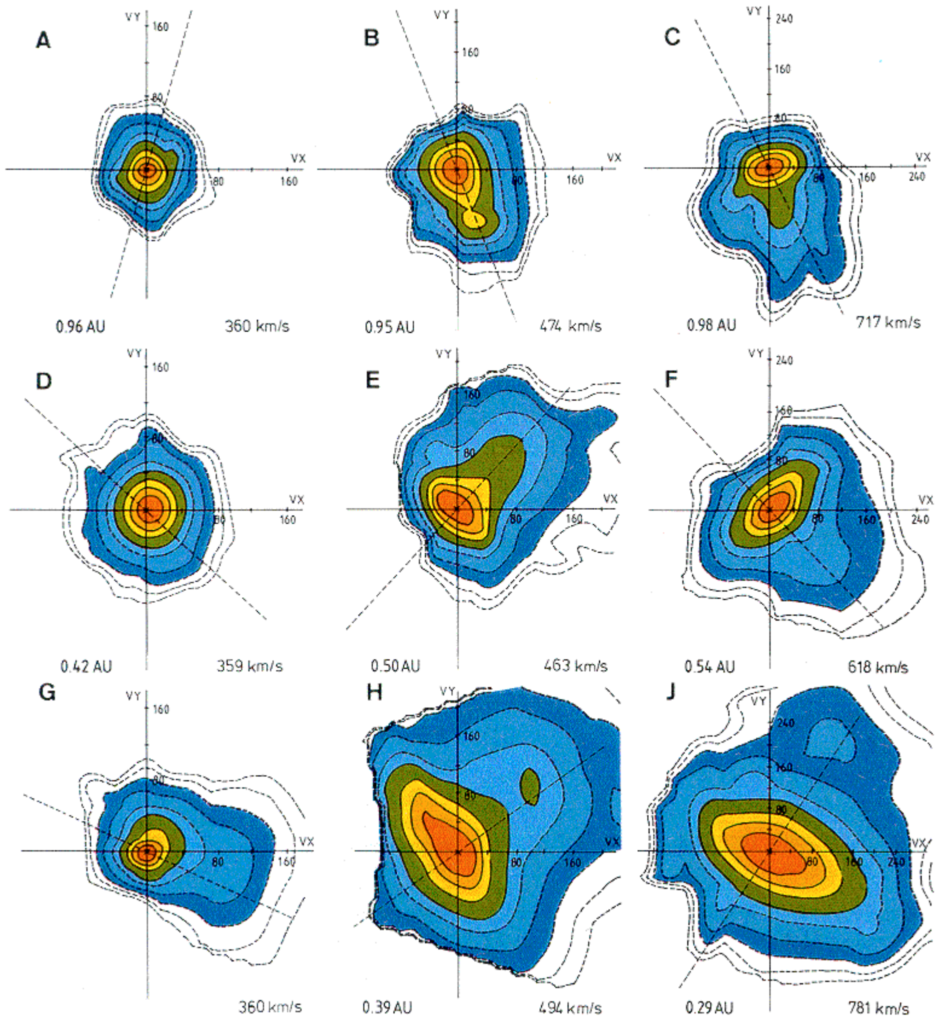
$\rightarrow$ **deviations from local thermal equilibrium**

$\rightarrow$ **suprathermal particles (electron strahl)**

$\rightarrow$ **global boundaries are reflected locally**

Problem: Thermodynamics of the plasma, which is far from equilibrium.....

Proton velocity distributions



- **Temperature anisotropies**
- **Ion beams**
- **Plasma instabilities**
- **Interplanetary heating**

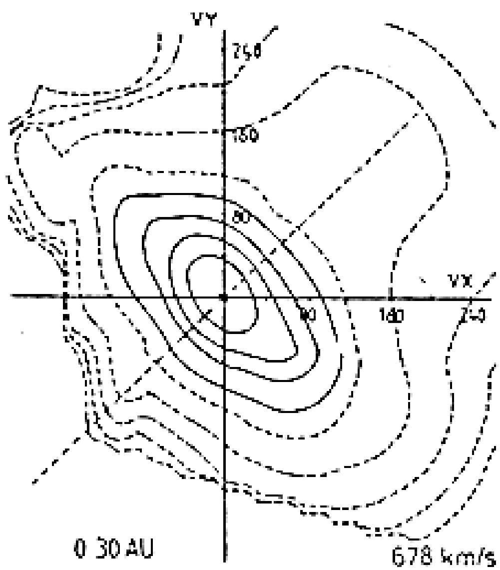
Plasma measurements made at 10 s resolution (> 0.29 AU from the Sun)

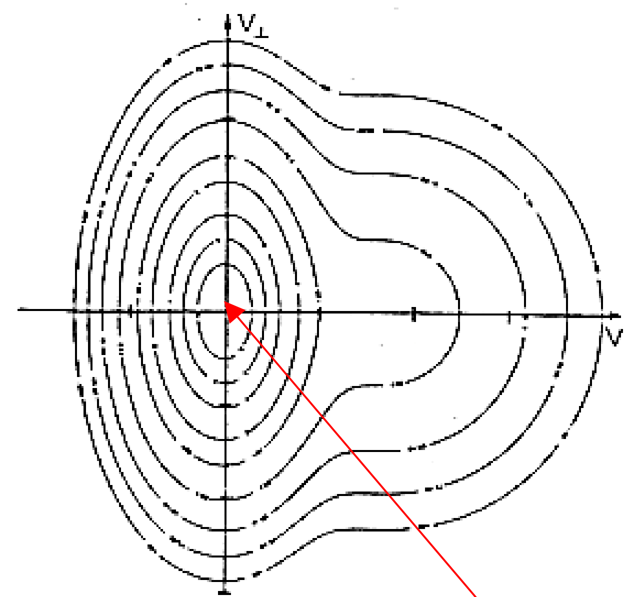
Helios

Marsch et al., JGR, **87**, 52, 1982

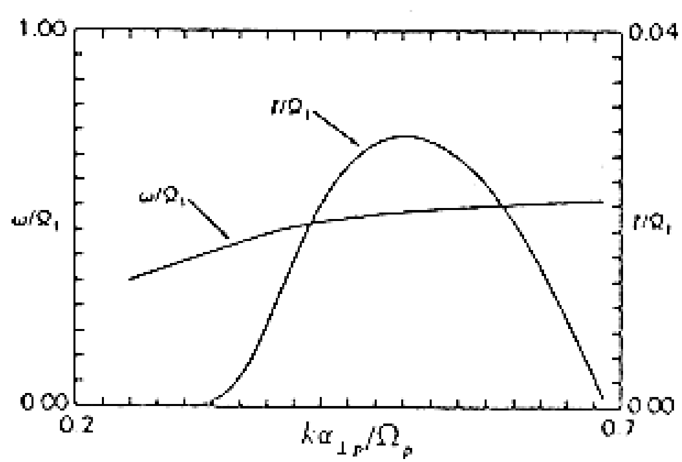
Proton temperature anisotropy

- Measured and modelled proton velocity distribution
- Growth of ion-cyclotron waves!
- Anisotropy-driven instability by large perpendicular $T_\perp$





anisotropy



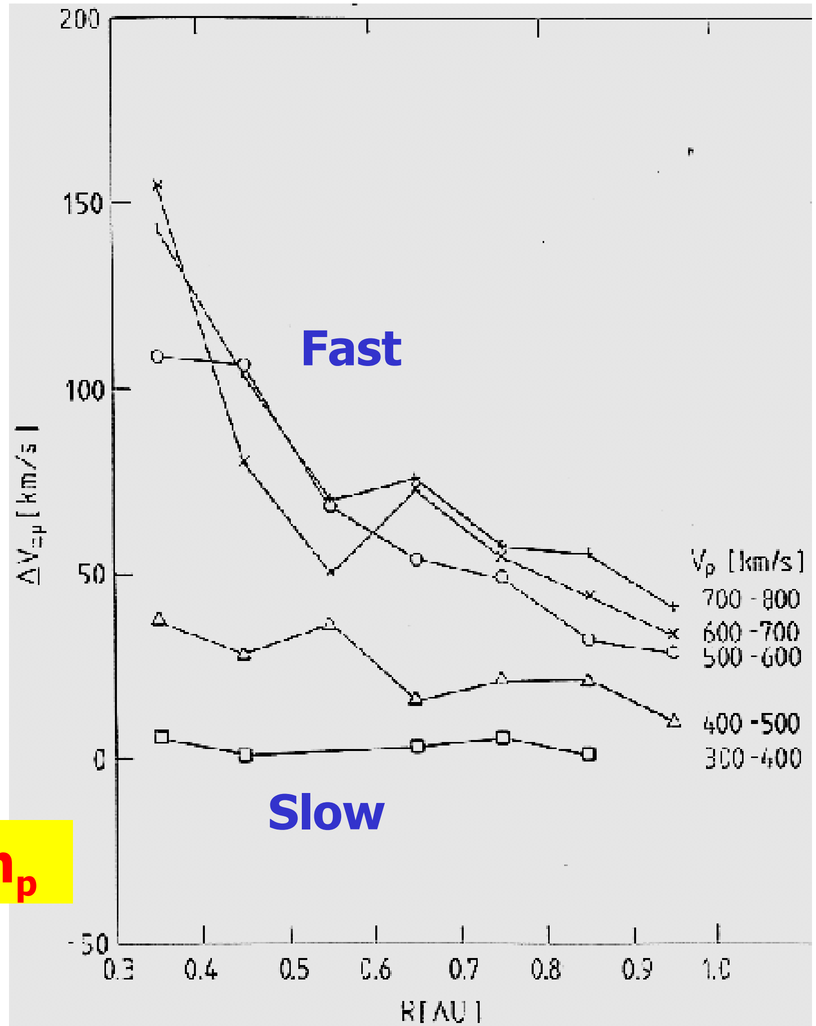
$\omega \approx 0.5\Omega_p$

$\gamma \approx 0.05\Omega_p$

Marsch, 1991

Ion differential streaming

$\Delta\underline{\mathbf{V}}$ /kms^{-1}



$T_\alpha/T_p \geq m_\alpha/m_p$

Distance r /AU

- **Alpha particles are faster than the protons!**
- **In fast streams the differential velocity is: $\Delta\underline{\mathbf{V}} \leq \underline{\mathbf{V}}_A$**
- **Heavy ions travel at alpha-particle speed**

Marsch et al., JGR, **87**, 52, 1982

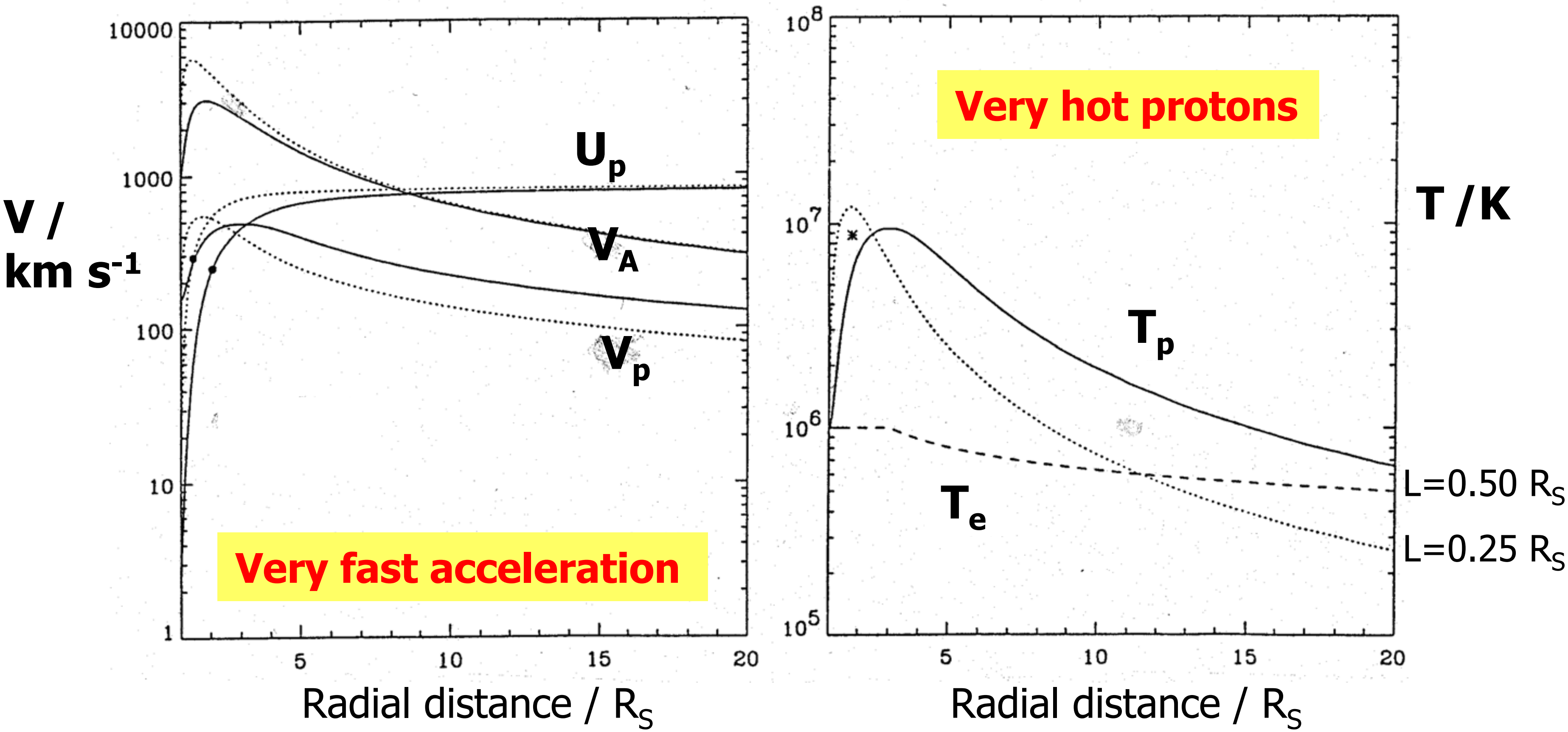
Fluid equations

- **Mass flux:** $F_M = \rho V A \qquad \rho = n_p m_p + n_i m_i$
- **Magnetic flux:** $F_B = B A$
- **Total momentum equation:**

$$V \, d/dr \, V = - 1/\rho \, d/dr \, (p + p_w) - G M_S / r^2 + a_w$$

- **Thermal pressure:** $p = n_p k_B T_p + n_e k_B T_e + n_i k_B T_i$
- **MHD wave pressure:** $p_w = (\delta B)^2 / (8\pi)$
- **Kinetic wave acceleration:** $a_w = (\rho_p a_p + \rho_i a_i)/\rho$
- **Stream/flux-tube cross section:** $A(r)$

Rapid acceleration of the high-speed solar wind



McKenzie et al., A&A, **303**, L45, 1995

Heating: $Q = Q_0 \exp(-(r - R_S)/L)$; Sonic point: $r \approx 2 R_S$

Important questions

- How is the Sun‘s magnetic field generated?

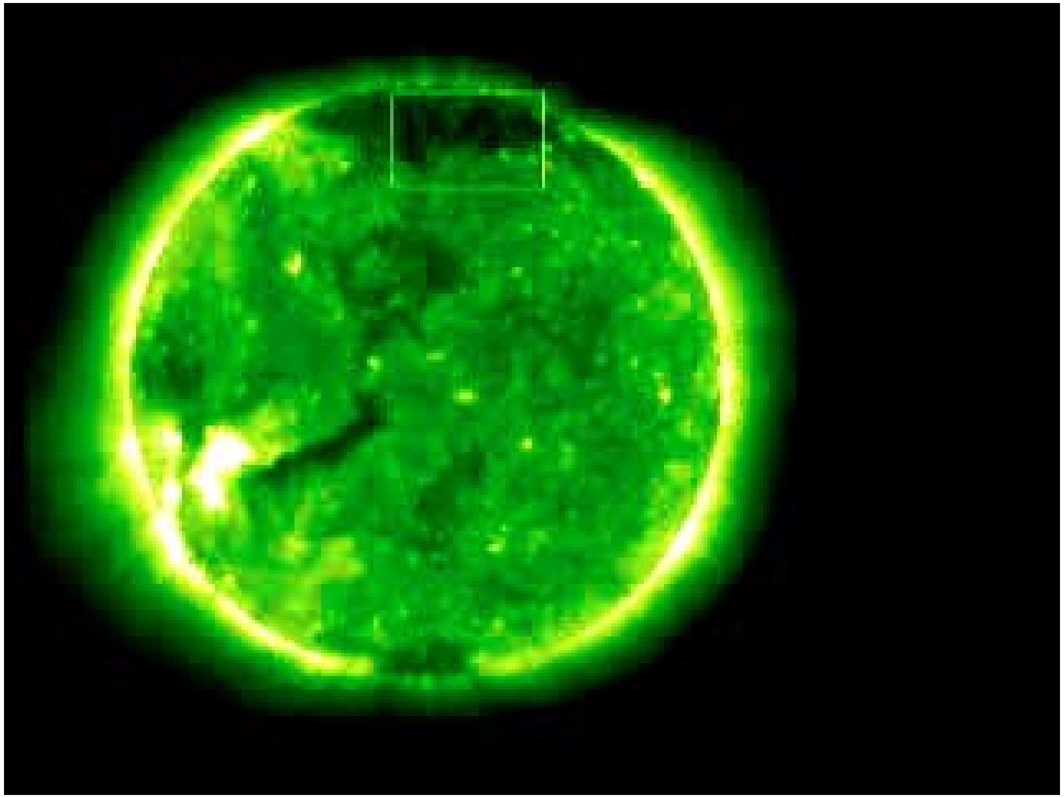
- How are the slow wind and CMEs accelerated?

- How is the solar corona heated?

- How is plasma turbulence generated and dissipated?

On the source regions of the fast solar wind in coronal holes

Image: EIT
Corona in
Fe XII 195 Å
at 1.5 M K



Insert: SUMER
Ne VIII 770 Å
at 630 000 K

Chromospheric
network
Doppler shifts
Red: down
Blue: up

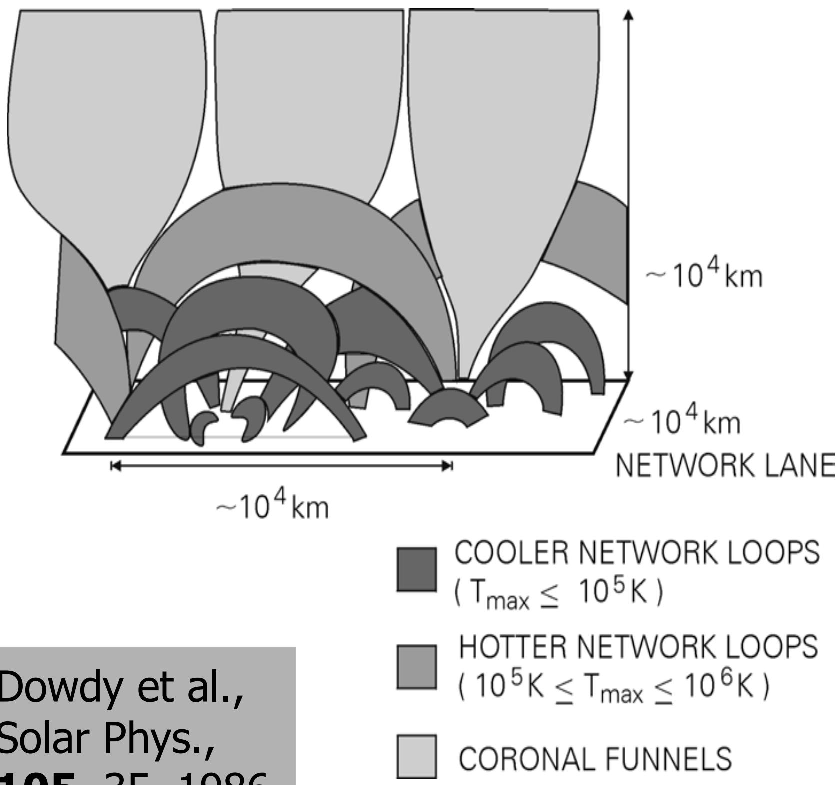
Outflow at
lanes and
junctions

Hassler et al.,
Science 283,
811-813, 1999

Magnetic network loops and funnels

Structure of transition region

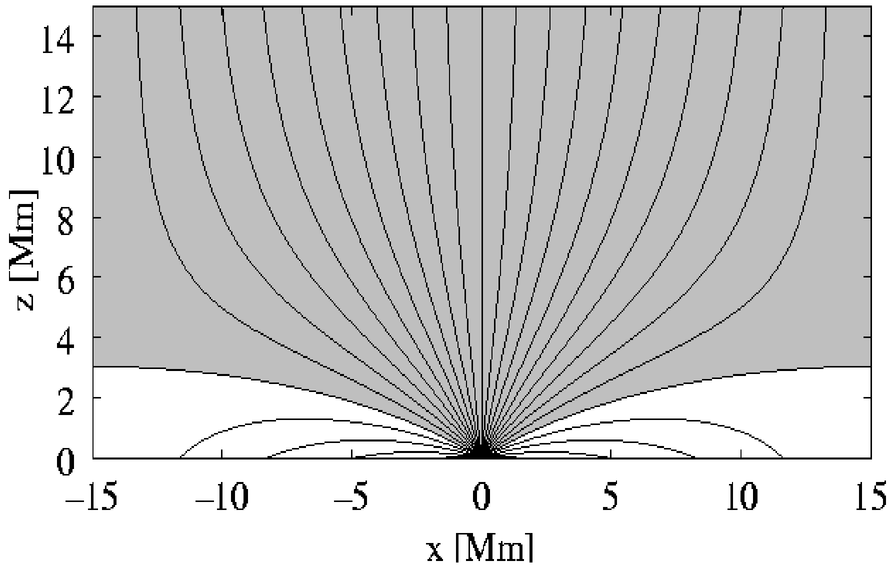
$F_B = AB$ $F_M = A\rho V$



Dowdy et al., Solar Phys., **105**, 35, 1986

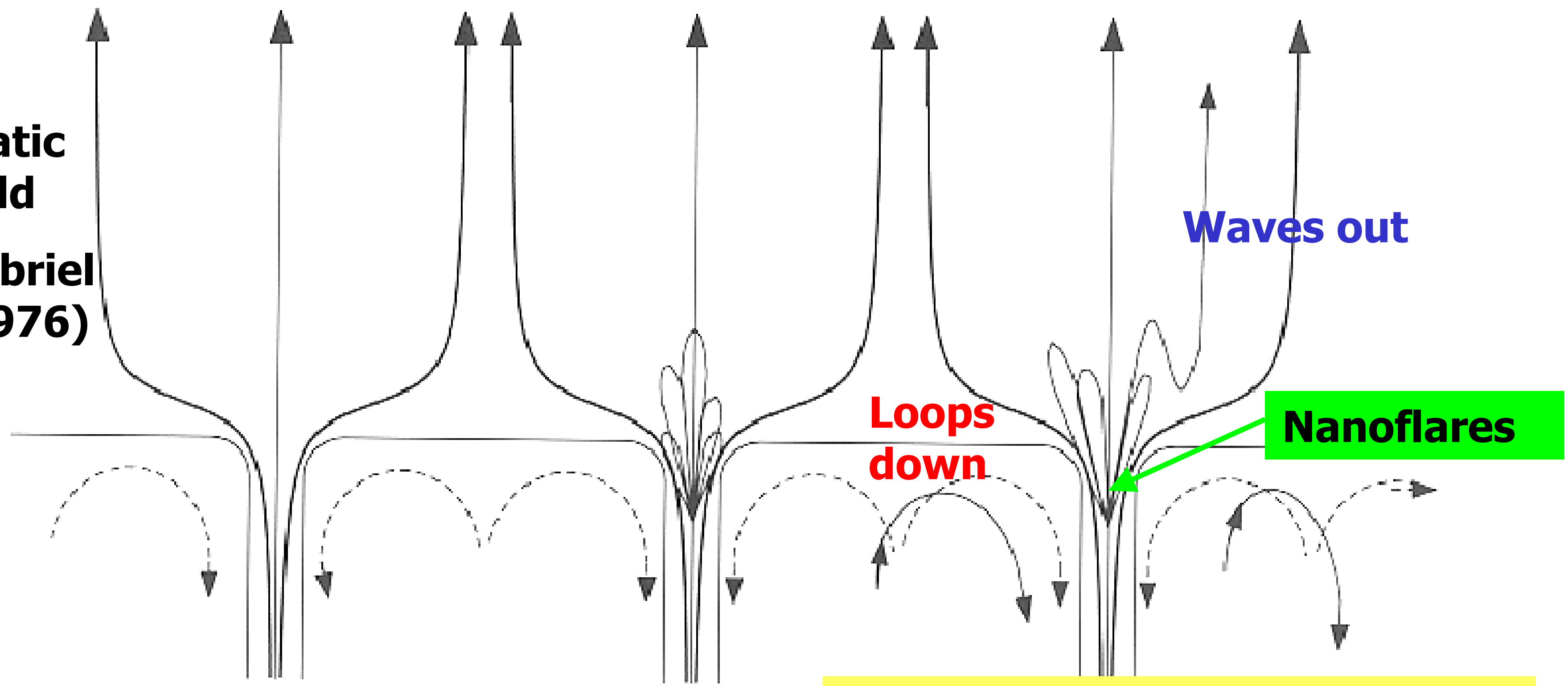
Magnetic field of coronal funnel

A(z) = flux tube cross section



Hackenberg et al., Space Sci. Rev., **87**, 207, 1999

Dynamic network and magnetic furnace by reconnection

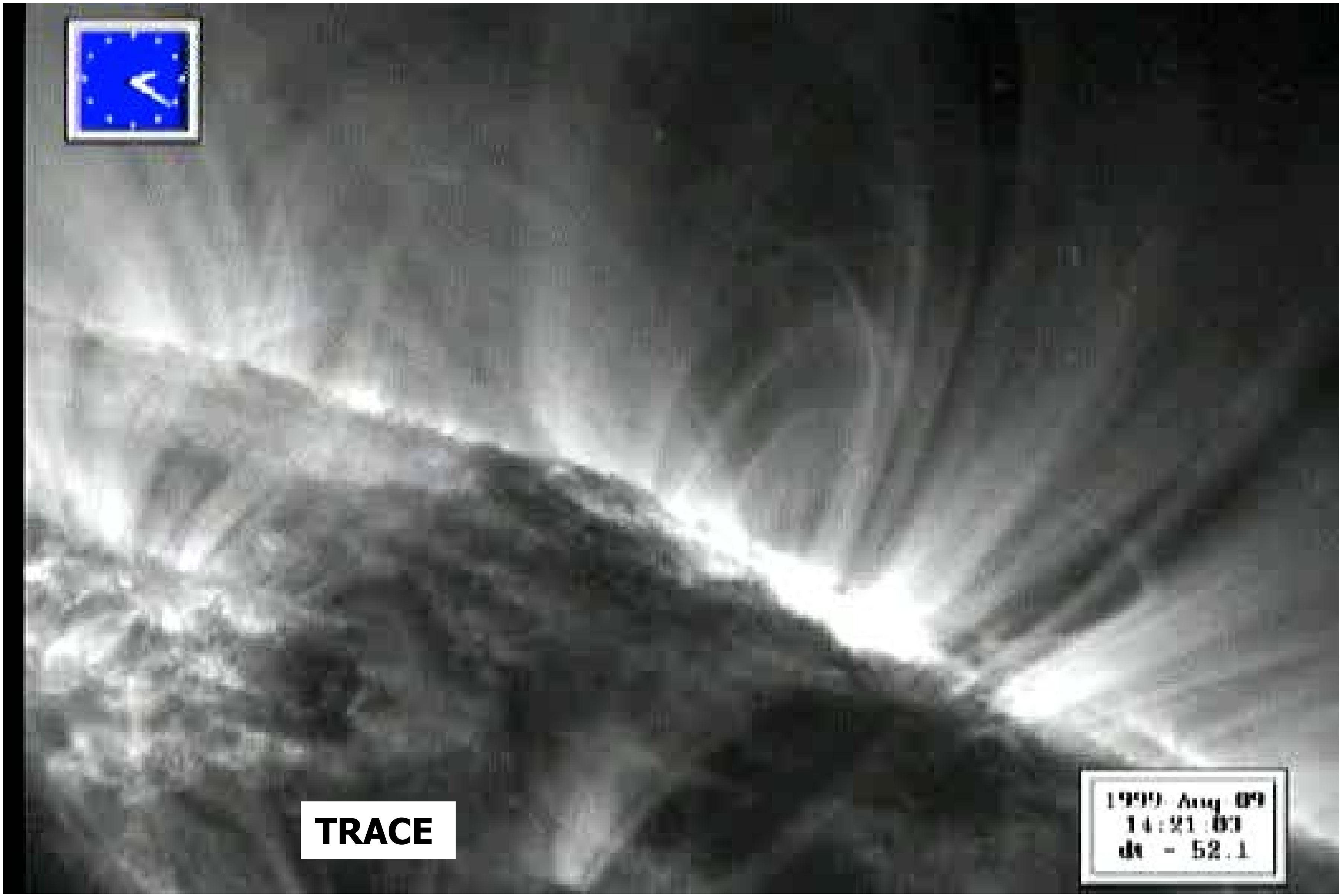


New flux fed in at sides by convection (t ~ 20 minutes)

$F_E = 10^7$ erg cm^{-2} s^{-1}

Axford and McKenzie, 1992, and Space Science Reviews, **87**, 25, 1999

Evolution of magnetic loops



Kinetic plasma instabilities

- Observed velocity distributions at margin of stability
- Selfconsistent quasi- or non-linear effects not well understood
- Wave-particle interactions are the key to understand ion kinetics in corona and solar wind!

Wave mode	Free energy source
Ion acoustic	Ion beams, electron heat flux
Ion cyclotron	Temperature anisotropy
Whistler (Lower Hybrid)	Electron heat flux
Magnetosonic	Ion beams, differential streaming

Marsch, 1991; Gary, Space Science Rev., **56**, 373, 1991

Energy equations

Parallel thermal energy

$$\frac{d}{dr}v_{\|j}^2 = -2v_{\|j}^2\left(\frac{1}{u_j}\frac{du_j}{dr}\right) + \frac{2q_{\|j}}{u_j} + (Q_{\|j} + S_{\|j})/u_j$$

w-p terms + sources + sinks

Perpendicular thermal energy

$$\frac{d}{dr}v_{\perp j}^2 = -v_{\perp j}^2\left(\frac{1}{A}\frac{dA}{dr}\right) + \frac{q_{\perp j}}{u_j} + (Q_{\perp j} + S_{\perp j})/u_j$$

Heating functions: $q_{\perp,\|}$ .... ?

Wave energy absorption/emission by wave-particle interactions !

Conduction/collisional exchange of heat + radiative losses